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ВЫСОКИХ ТЕХНОЛОГИЙ

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ԲԱՐՁՐ ՏԵԽՆՈԼՈԳԻԱՆԵՐԻ ՏԵՂԵԿԱԳԻՐ
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AN ALGORITHM FOR DYNAMIC CHANGE OF INFORMATION TRANSMISSION CHANNELS IN AD-HOC IoT NETWORKS AND ITS PLACE AMONG EXISTING APPROACHES

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Abstract

A classification of existing algorithms for dynamic change of network structures in ad-hoc IoT networks is provided. The proposed algorithm for dynamic change of information transmission channels is described, and its position among existing approaches is established.

The algorithm employs Dijkstra’s shortest path method with a composite cost function integrating five weighted factors: residual node energy, inter-node distance, wireless link quality, node traffic load, and link congestion. A Python-based discrete-event simulation framework built on SimPy and NetworkX is developed to evaluate the proposed algorithm against four established routing protocols: shortest-path (hop-count), AODV, LEACH-C, and energy-aware routing. The results of conducted research and their comparative analysis are presented.

Comprehensive experiments across five scenarios involving 30 independent trials with 50 nodes demonstrate that the proposed multi-criteria algorithm achieves the highest packet delivery ratio of 98.9% in stationary networks and 96.9% in mobile environments, while maintaining competitive latency and energy fairness. Scalability tests with up to 200 nodes confirm sustained performance advantages. The advantage of using the proposed algorithm for network structure change is demonstrated according to various criteria, including packet delivery ratio, network lifetime, and energy fairness. The commonalities among all tested algorithms are discussed, and conclusions of the work are presented.

Key words: ad-hoc networks, dynamic topology management, multi-criteria routing, IoT mesh network simulation, energy-aware routing, Dijkstra algorithm, wireless sensor networks, discrete-event simulation.

Bulletin Of High Technology N 1 (37) 2026.-pp.3-18.

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AN ALGORITHM FOR DYNAMIC CHANGE OF INFORMATION TRANSMISSION CHANNELS IN AD-HOC IoT NETWORKS AND ITS PLACE AMONG EXISTING APPROACHES

Introduction

Relevance of the work. The rapid proliferation of Internet of Things (IoT) devices has created an urgent need for robust, self-organizing wireless mesh networks capable of operating in dynamic environments. IoT mesh networks, built on standards such as IEEE 802.15.4 (ZigBee), IEEE 802.11s, and Thread, enable multi-hop communication where sensor nodes cooperatively forward data packets toward a destination. Unlike centralized star topologies, mesh networks offer inherent redundancy and extended coverage, making them particularly suitable for large-scale deployments in smart cities, environmental monitoring, industrial automation, and precision agriculture [1, 2].

A critical aspect of these networks is the dynamic nature of their topology. Nodes continuously deplete their limited battery reserves, experience hardware failures, or physically relocate. When a relay node fails, all routes traversing that node become invalid, potentially partitioning the network and causing significant packet loss. Existing routing protocols for ad-hoc networks, such as AODV [5] and OLSR [6], optimize primarily for hop count or link state without considering the heterogeneous and time-varying nature of IoT node resources. This creates energy hotspots at central relay nodes, accelerating their failure and reducing overall network lifetime. The development of routing algorithms that simultaneously account for multiple dynamic network parameters—energy, distance, link quality, load, and congestion—remains an open and relevant research problem [3, 4].

Issues under consideration. This work addresses the following research questions: (1) How can multiple criteria—node energy, physical distance, wireless link quality, traffic load, and link congestion—be integrated into a single cost function for routing decisions in IoT mesh networks? (2) How does the proposed multi-criteria algorithm compare against established routing protocols (shortest-path, AODV, LEACH-C, and energy-aware routing) in terms of packet delivery ratio, network lifetime, energy fairness, and latency? (3) How does the algorithm perform under varying conditions, including network scale (12–200 nodes), node mobility (0–10 m/s), and different traffic patterns? (4) Can adaptive weight tuning improve performance compared to fixed weight configurations?

Structure of the article. The remainder of this paper is organized as follows. Section 2 reviews existing routing algorithms for ad-hoc networks and establishes their classification. Section 3 describes the proposed multi-criteria algorithm, including its cost function and adaptive weight mechanism. Section 4 presents the discrete-event simulation framework used for evaluation. Section 5 provides experimental results and comparative analysis across five scenarios. Section 6 discusses commonalities among the tested algorithms. Section 7 establishes the classification and position of the proposed approach among existing methods, and Section 8 concludes the paper.

Review and Classification of Existing Routing Algorithms

Routing protocols for wireless ad-hoc and sensor networks can be classified along several dimensions: proactive versus reactive route discovery, flat versus hierarchical topology, and single-criterion versus multi-criteria path selection [3, 8]. This section reviews the four algorithms used as comparison benchmarks in this study.

Shortest-Path Routing (Hop-Count Dijkstra). The baseline approach uses Dijkstra’s algorithm to find the path with the minimum number of hops between source and destination. This method is computationally efficient and produces optimal paths in terms of hop count. However, it is oblivious to node energy levels, link quality, and traffic load. In dense networks, shortest-path routing consistently directs traffic through central relay nodes, creating “bottleneck nodes” that deplete their batteries significantly faster than peripheral nodes. In our experiments, shortest-path routing achieved a PDR of 96.8% with the worst energy fairness (Jain’s index 0.856) among all tested algorithms [9].

AODV (Ad-hoc On-Demand Distance Vector). AODV, defined in RFC 3561 [5], is a reactive protocol that discovers routes only when a data packet needs to be sent. The source node broadcasts a Route Request (RREQ) message that propagates through the network; the destination replies with a Route Reply (RREP) along the reverse path. Routes are maintained with sequence numbers to prevent loops and detect stale entries. The reactive nature of AODV minimizes control overhead during idle periods but introduces route discovery latency of 100–500 ms for the first packet on each new route. AODV performs well in mobile scenarios due to its ability to rapidly discover fresh routes [10].

LEACH-C (Low-Energy Adaptive Clustering Hierarchy – Centralized). LEACH-C [7] organizes nodes into clusters, each managed by a cluster head selected based on residual energy. Regular nodes transmit to their nearest cluster head, which aggregates data and forwards it toward the sink. Cluster heads are re-elected periodically (every 30 seconds in our implementation) to distribute the energy burden. LEACH-C achieves the best energy fairness (Jain’s index 0.922) among the tested algorithms but introduces a minimum two-hop latency (node → cluster head → destination path) and higher average delay [7, 11].

Energy-Aware Routing. This approach selects routes that maximize the minimum residual energy among all nodes on the path (max-min energy criterion). By protecting the weakest node on any candidate path, energy-aware routing is effective at delaying the first node failure. In our stationary experiments, it achieved first-node-death at 86 seconds compared to 62 seconds for shortest-path routing. However, by considering only energy, this approach ignores link quality, distance, and congestion, resulting in suboptimal PDR (98.1%) compared to the multi-criteria approach [12, 13].

Proposed Multi-Criteria Routing Algorithm

The proposed algorithm extends Dijkstra’s shortest path algorithm with a composite cost function that evaluates each link across five criteria. The cost of traversing a link from node i to node j is defined as:

$$C(i,j) = w_1/E_j + w_2\cdot(d_{ij}/100) + w_3/Q_{ij} + w_4\cdot L_j\cdot 2 + w_5\cdot\Gamma_{ij}, \qquad (1)$$

where E_j is the residual energy ratio of node j (0 to 1), d_{ij} is the Euclidean distance between nodes i and j, Q_{ij} is the link quality (0.3 to 1.0), L_j is the traffic load of node j (0 to 1), and Γ_{ij} is the congestion level of the link (0 to 1). The weights w_1 through w_5 are configured as shown in Tab 1.

Bulletin Of High Technology N 1 (37) 2026.-pp.3-18.

Table 1

Default weight configuration for the multi-criteria cost function

Factor	Weight	Rationale
1/Energy	0.30	Avoids low-battery nodes; cost triples as energy drops from 60% to 20%
Distance/100	0.20	Prefers shorter hops to reduce path loss and energy consumption
1/Quality	0.20	Penalizes unreliable wireless links with high error rates
Load × 2	0.20	Distributes traffic away from overloaded relay nodes
Congestion	0.10	Avoids congested links to reduce queuing delays

The total path cost is the sum of individual link costs along the route. The algorithm uses Dijkstra’s algorithm with a priority queue to find the minimum-cost path from source to destination, considering only active nodes. Routes are cached with a time-to-live (TTL) of 10 seconds; expired routes trigger recomputation to adapt to changing network conditions.

Adaptive Weight Mechanism. The algorithm incorporates an optional adaptive weight-tuning mechanism that adjusts the five cost weights based on real-time network state. Every 10 seconds, the algorithm evaluates average node energy, average congestion, average load, and average link quality across the network. When average energy falls below 60%, the energy weight is scaled up linearly (up to 2.5× at 10% average energy). Similar scaling applies to congestion (threshold: 30%), load (threshold: 40%), and quality (threshold: 60%). After scaling, weights are renormalized to sum to 1.0. This mechanism ensures that the algorithm shifts its optimization priority toward the most critical network resource as conditions evolve.

Simulation Framework

The simulation environment is implemented in Python using SimPy 4.0 for discrete-event modeling and NetworkX 3.0 for graph algorithms and topology management. The framework models a complete IoT mesh network with realistic physical-layer characteristics. Fig. 1 illustrates the two-step network construction process: random node placement followed by mesh topology formation based on communication range.

Network Model. Nodes are deployed randomly in a 400×400 m area. Each node is modeled as a battery-powered IoT sensor with initial energy uniformly distributed between 0.3 and 0.5 Joules, following the energy model conventions established by Heinzelman et al. [7] for wireless sensor network simulations. Nodes within a mesh range of 150 m (tyFigal outdoor ZigBee range) form bidirectional wireless links, creating a partial mesh topology. The network supports node mobility using a random waypoint model with configurable speed and mobile fraction [14, 15].

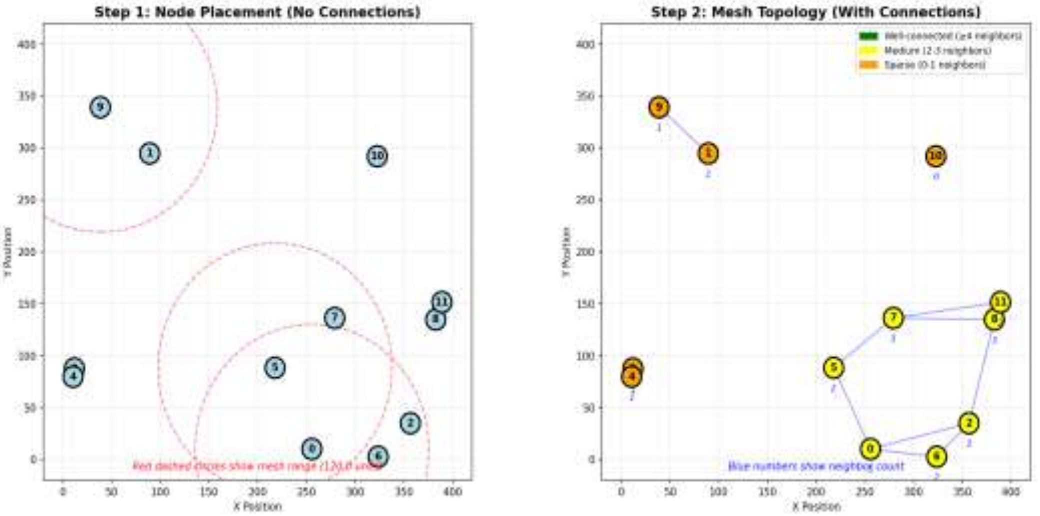

Fig. 1 Network construction: (a) random node placement with 150 m communication range circles; (b) resulting mesh topology with connectivity indicators

Fig. 2 shows the final state of the network at the end of a 100-second simulation, where nodes are colored by energy level and the metrics panel displays key performance indicators including PDR, average latency, and average hop count.

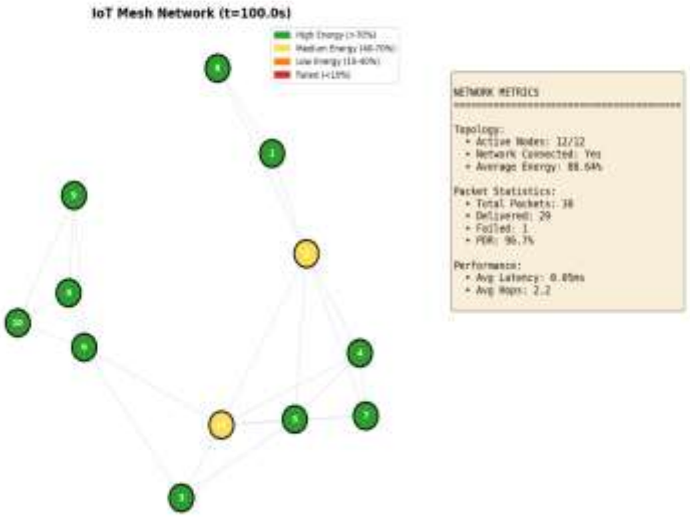

Fig. 2 Network state at t = 100 s: nodes colored by residual energy (green > 70%, yellow 40–70%, orange 10–40%, red = failed), with network performance metrics

Energy Model. Energy consumption follows the first-order radio model [7]:

$$E_{tx}(k,d) = E_{elea} \cdot k + E_{amp} \cdot k \cdot d^n \quad (2)$$

where E_{elea} = 50 nJ/bit is the electronics energy, k = 8192 bits (1024-byte packet), and the amplifier energy E_{amp} uses the free-space model (10 pJ/bit/m²) for distances below the crossover distance d_0 = 87 m and the multi-path model (0.0013 pJ/bit/m⁴) for longer distances. Receive energy is $E_{rx} = E_{elea} \cdot k$. Nodes fail when residual energy drops below 5% of initial capacity and have a 5% per-second chance of recovery (simulating energy harvesting or battery replacement) [7, 16].

Wireless Channel Model. The log-distance path loss model is used:

$$PL(d) = PL(d_0) + 10n \cdot \log_{10}(d/d_0) + X\sigma, \tag{3}$$

with reference path loss $PL(d_0) = 40$ dB at 1 m, path loss exponent $n = 2.5$ (tyFigal outdoor), and Gaussian shadow fading $X\sigma$ with standard deviation 3 dB. Packet success probability is computed using a sigmoid function of the signal margin above receiver sensitivity (−100 dBm, tyFigal 802.15.4), multiplied by the current link quality factor [17].

Packet Transmission. Packets are transmitted hop-by-hop along the computed route. At each hop, the simulator models MAC-layer retransmission with up to 3 retry attempts. A packet is marked as failed if any hop exhausts its retries or if the next-hop node has failed. Link congestion increases by 0.1 per packet and decays at 10% per second. Link quality fluctuates randomly within ±0.02 per second, bounded between 0.3 and 1.0 [14].

Evaluation Metrics. To assess energy distribution fairness across the network, we use Jain’s fairness index [7], defined as:

$$J(x_1, x_2, ..., x_n) = (\Sigma x_i)^2 / (n \cdot \Sigma x_i^2), \tag{4}$$

where x_i represents the energy ratio (residual/initial) of node i and n is the total number of active nodes. The index ranges from 1/n (maximally unfair, all energy consumed by one node) to 1.0 (perfectly fair, all nodes have equal energy). A higher value indicates more equitable energy consumption across the network. This metric, originally proposed by Jain et al. (1984) for measuring resource allocation fairness in computer networks, is widely used in wireless sensor network research to evaluate how evenly routing algorithms distribute the communication burden.

Experimental Results and Comparative Analysis

Five experiments were conducted to evaluate the proposed algorithm from different perspectives. Each experiment consists of 30 independent trials with different random seeds to ensure statistical robustness. The default configuration uses 50 nodes deployed in a 400×400 m area with 150 m mesh range. The five algorithms compared are: Multi-Criteria (MC), Shortest Path (SP), AODV, LEACH-C (LC), and Energy-Aware (EA).

Experiment 1: Algorithm Comparison. Table 2 presents the performance of all five algorithms under stationary and mobile (5 m/s) conditions.

The multi-criteria algorithm achieves the highest PDR (98.88%) in stationary conditions, outperforming shortest-path routing by 2.04 percentage points. In mobile environments at 5 m/s, AODV’s reactive nature provides a slight advantage (97.83% vs. 96.89%), as on-demand route discovery naturally adapts to topology changes caused by node movement. LEACH-C achieves the best energy fairness (0.922) in stationary conditions due to its cluster-head rotation mechanism.

Table 2

Algorithm comparison results (50 nodes, 30 trials)

Algorithm	PDR (%) Stat.	PDR (%) Mobile	Latency (ms) Stat.	Fairness Stat.	Fairness Mobile
Multi-Criteria	98.88	96.89	45.3	0.896	0.968
Energy-Aware	98.12	96.87	46.6	0.891	0.967
AODV	97.63	97.83	45.1	0.883	0.929
LEACH-C	97.66	97.24	53.0	0.922	0.967
Shortest Path	96.84	96.62	45.9	0.856	0.893

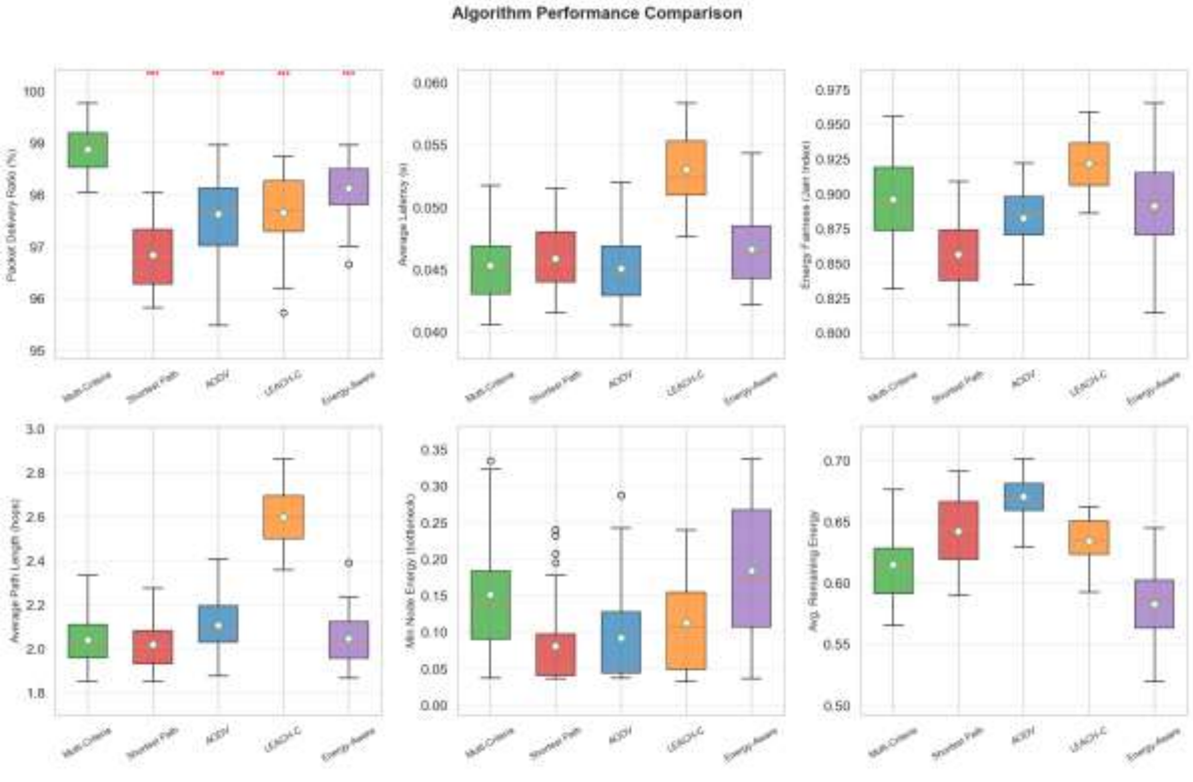

Fig. 3 Algorithm comparison: PDR, latency, and energy metrics across five routing protocols (stationary, 50 nodes, 30 trials)

Experiment 2: Scalability (12 to 200 nodes). Network size was varied from 12 to 200 nodes to assess scalability. At 200 nodes in stationary conditions, the multi-criteria algorithm maintains 99.0% PDR with 86 ms average latency, compared to 98.0% PDR for shortest-path and 96.4% for energy-aware routing. Under mobility, all algorithms experience significant degradation at scale, but the multi-criteria algorithm retains the highest PDR at 87.9% versus 83.0% for both shortest-path and energy-aware alternatives. These results confirm that the multi-criteria cost function scales effectively to larger networks.

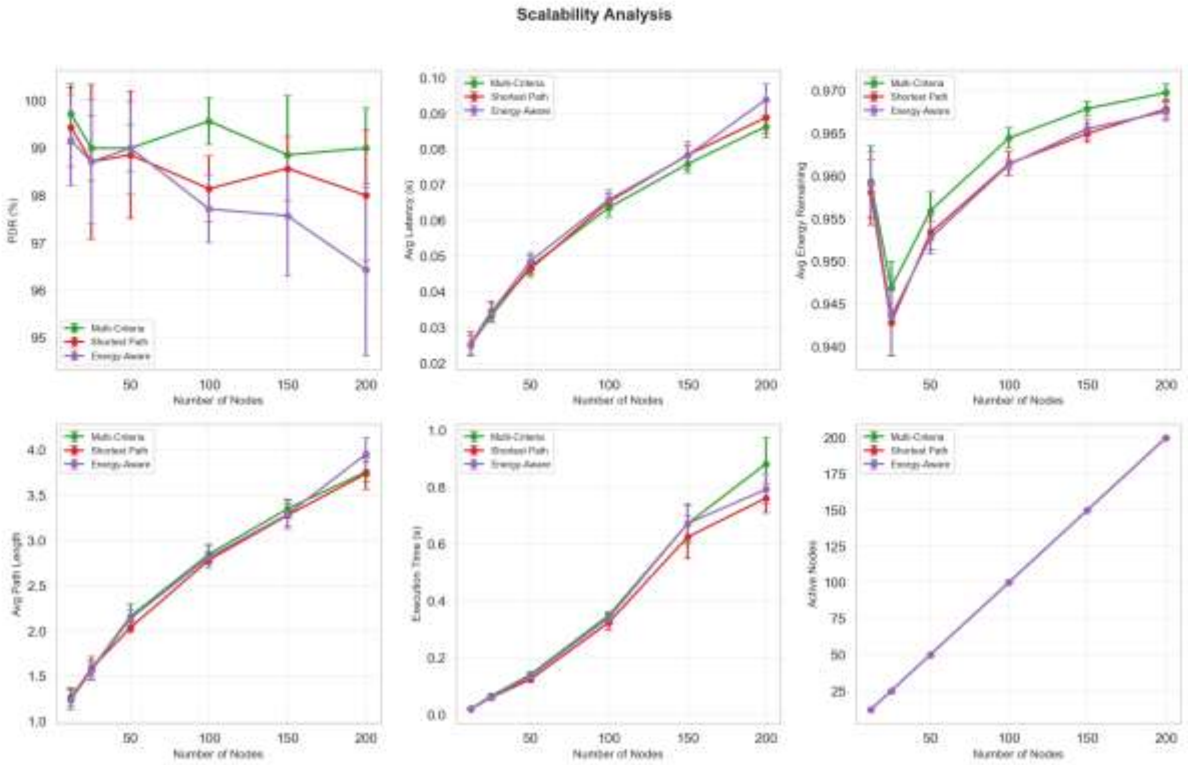

Fig. 4 Scalability analysis: PDR and latency as a function of network size (12–200 nodes)

Experiment 3: Network Lifetime. Network lifetime is measured by two thresholds: time to first node death and time until 25% of nodes have failed. Tab. 3 summarizes the results.

Table 3

Network lifetime comparison (seconds)

Algorithm	1st Death (Stat.)	25% Dead (Stat.)	1st Death (Mobile)	25% Dead (Mobile)
Multi-Criteria	~107	~175	~94	~184
Energy-Aware	~86	~170	~101	~184
LEACH-C	~60	~200	~80	~237
Shortest Path	~62	~180	~63	~206

Network lifetime is evaluated using first node death and the 25% failure threshold rather than complete network death, because in multi-hop wireless sensor networks the loss of critical relay nodes causes network partitioning and connectivity collapse long before all nodes exhaust their batteries. Consequently, the network becomes functionally inoperable well before 100% node failure, making partial failure thresholds more practical and widely adopted metrics in WSN literature [3, 16]. The multi-criteria algorithm delays first node death the longest in stationary conditions (107 s), exceeding energy-aware routing by 24% and shortest-path by 73%. This is because the multi-criteria cost function penalizes low-energy nodes, distributing traffic more evenly. LEACH-C achieves the best long-term survival (25% threshold at 200–237 s) due to its periodic cluster-head rotation, which fundamentally redistributes the energy burden [7].

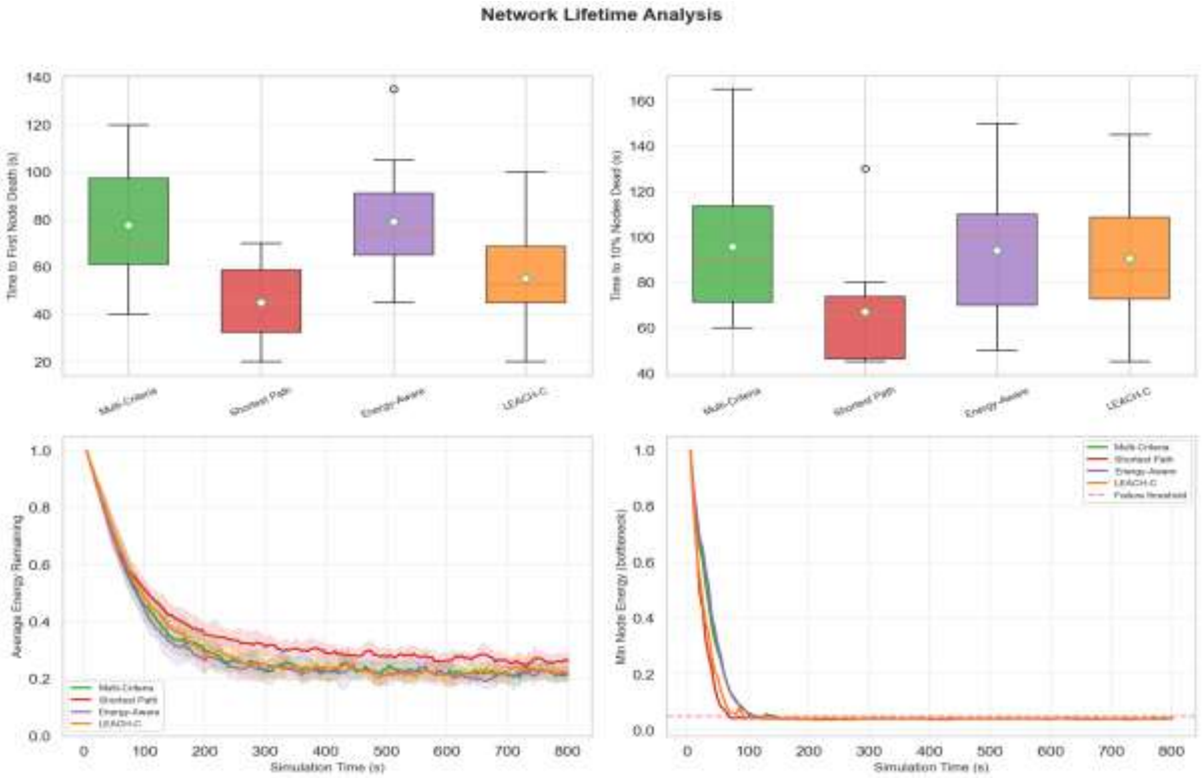

Fig. 5 Network lifetime: cumulative node failures over time for each algorithm

Experiment 4: Mobility Impact. Node speed was varied from 0 to 10 m/s to assess mobility resilience. At 10 m/s, AODV achieves the highest PDR (96.57%) owing to its reactive route discovery, followed by energy-aware (95.67%) and multi-criteria (94.83%). The multi-criteria algorithm degrades approximately 4% from stationary to 10 m/s mobility, while shortest-path degrades most severely. The 10-second route cache TTL becomes a limiting factor at high speeds, as cached routes may reference nodes that have moved out of range [10].

Experiment 5: Adaptive vs. Fixed Weights. The adaptive weight mechanism provides marginal improvement (1–2% in energy fairness) over the fixed default weights in most scenarios. Over a 600-second simulation, the energy weight increases from 0.300 to 0.418 (stationary) and 0.425 (mobile) as batteries deplete, while distance and quality weights decrease correspondingly. The adaptation is more pronounced in mobile networks where conditions change more rapidly.

The results confirm that the default weight configuration is near-optimal for tyFigal deployments, while the adaptive mechanism provides a safety margin for extended operation [18].

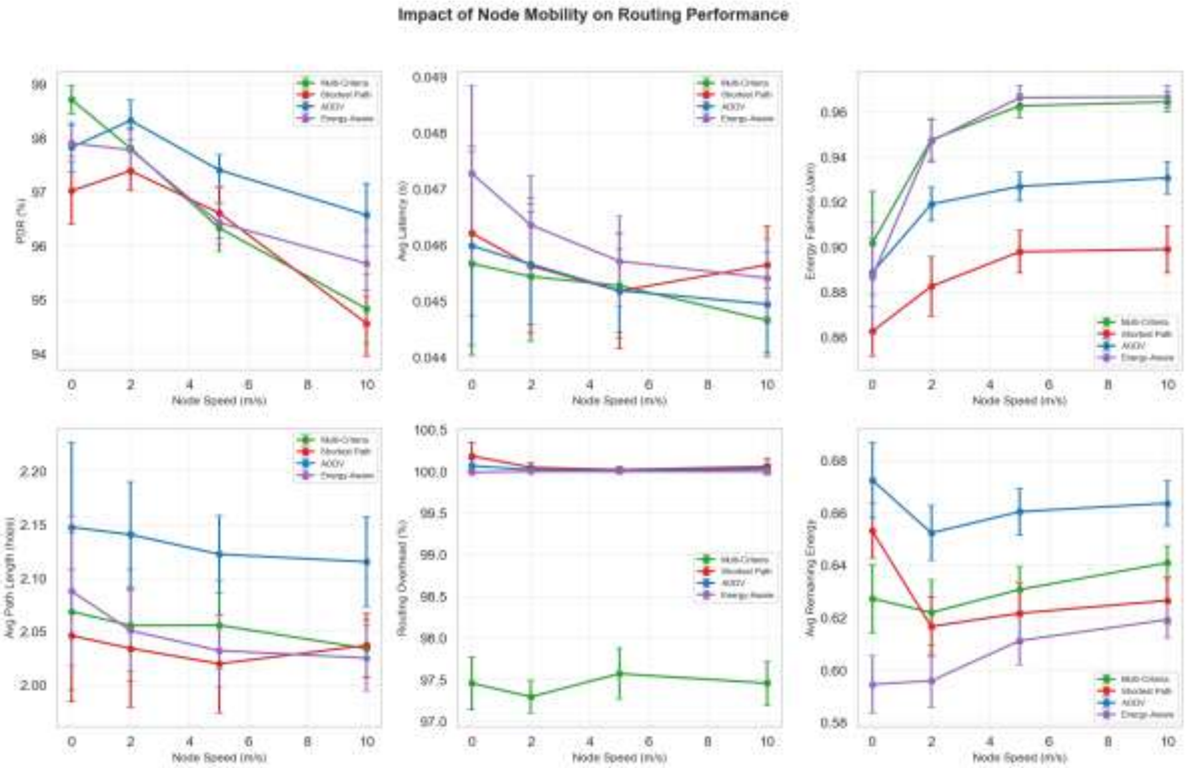

Fig. 6 Impact of node mobility speed (0–10 m/s) on PDR and energy fairness

Fig. 7 Adaptive weight evolution over 600 seconds: energy weight increases as network depletes

Commonalities of the Algorithms

Despite their differing strategies, all five routing algorithms share several fundamental properties that arise from the common problem domain of multi-hop wireless communication in resource-constrained networks.

First, all algorithms rely on a graph-based representation of the network topology, where nodes correspond to IoT devices and edges correspond to wireless links within communication range. The routing decision in every case reduces to a path selection problem on this graph. Dijkstra's algorithm or its variants (breadth-first search for unweighted graphs) serves as the computational backbone for four of the five algorithms; only LEACH-C departs from pure shortest-path computation by introducing a hierarchical cluster structure [3, 7].

Second, all algorithms exhibit sensitivity to network density. In sparse networks (fewer than 20 nodes in a 400×400 m area), all algorithms converge toward similar performance because routing options are limited—often only one or two paths exist between any source-destination pair. The differentiation between algorithms becomes meaningful only when the network provides sufficient path diversity, tyFigally above 30–40 nodes in the tested deployment area [8].

Third, all algorithms benefit from mobility in terms of energy fairness. When nodes move, the set of relay nodes changes over time, naturally distributing the forwarding burden across a larger subset of the network. This was observed consistently across all experiments: energy fairness (Jain's index) improved under mobility for every algorithm, from 0.856–0.922 (stationary) to 0.893–0.968 (mobile at 5 m/s). This suggests that mobility, while challenging for route stability, has an inherent load-balancing effect that complements algorithmic optimization [10].

Fourth, all algorithms share the fundamental trade-off between route optimality and route freshness. Proactive algorithms (multi-criteria, shortest-path, energy-aware) maintain continuously updated routing tables but may use stale information between updates. The multi-criteria algorithm addresses this with a 10-second cache TTL. Reactive algorithms (AODV) guarantee fresh routes but incur discovery latency. LEACH-C occupies a middle ground with periodic re-clustering every 30 seconds. No algorithm entirely resolves this trade-off; rather, each makes a different design choice along the optimality–freshness spectrum [5, 6].

Fifth, packet delivery ratio for all algorithms exceeds 96% under stationary conditions with 50 nodes, confirming that the underlying mesh topology with 150 m range and 400×400 m deployment provides sufficient connectivity for reliable communication regardless of the routing strategy.

The algorithms differentiate themselves primarily in their secondary effects: energy distribution, lifetime extension, and adaptation to dynamic conditions [9].

Classification and Position of the Proposed Algorithm

The proposed multi-criteria routing algorithm occupies a distinct position in the taxonomy of ad-hoc routing protocols. Table 4 classifies the tested algorithms across key dimensions.

The multi-criteria algorithm is the only approach that simultaneously considers energy conservation, path quality, load balancing, and congestion avoidance within a single unified framework. While each single-criterion algorithm excels in its specific dimension (energy-aware for lifetime,

Table 4

Classification of routing algorithms

Property	MC	SP	AODV	LEACH-C	EA
Discovery	Proactive	Proactive	Reactive	Hierarchical	Proactive
Criteria	5 factors	Hop count	Distance	Cluster dist.	Energy
Adaptive	Yes	No	No	Periodic	No
Best PDR	98.9%	96.8%	97.6%	97.7%	98.1%
1st Death (s)	107	62	N/A	60	86

AODV for mobility, LEACH-C for fairness), the multi-criteria approach provides the best overall balance across all metrics. The adaptive weight mechanism further distinguishes the proposed algorithm by enabling dynamic rebalancing of optimization priorities without manual intervention [3, 8].

The weight sensitivity analysis (varying all five weights across multiple configurations) demonstrates that the algorithm is robust to weight selection: PDR remains within a 0.4 percentage point range (98.7–99.1%) across all tested weight configurations in stationary conditions. This robustness suggests that the multi-criteria approach provides stable performance even without precise a priori knowledge of optimal weights.

Conclusion

This paper presented a multi-criteria routing algorithm for dynamic IoT mesh networks that integrates five weighted cost factors—residual energy, distance, link quality, traffic load, and congestion—into a Dijkstra-based path selection framework. A comprehensive discrete-event simulation environment was developed using SimPy and NetworkX to evaluate the algorithm against four established routing protocols across five experimental scenarios.

The experimental results lead to the following conclusions:

1. The multi-criteria algorithm achieves the highest packet delivery ratio (98.9%) in stationary networks, outperforming shortest-path routing by over 2 percentage points and energy-aware routing by 0.8 percentage points.
2. First node death is delayed to 107 seconds (stationary), representing a 73% improvement over shortest-path and 24% improvement over energy-aware routing, demonstrating effective bottleneck mitigation.
3. The algorithm scales well from 12 to 200 nodes, maintaining superior PDR at all tested network sizes in both stationary and mobile conditions.
4. The adaptive weight mechanism provides a self-tuning capability that increases the energy weight from 0.30 to 0.42 as batteries deplete, offering marginal but consistent improvements in energy fairness.

5. In high-mobility scenarios (10 m/s), reactive protocols such as AODV outperform the proposed approach, suggesting that future work should explore hybrid proactive-reactive strategies or reduced cache TTL values.

Future research directions include extending the algorithm with multipath routing for critical packets, integrating machine learning for weight prediction, and validating the simulation results on real hardware platforms such as ESP32 or nRF52 with ZigBee communication modules.

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AD-HOC IOT **ՑԱՆՑԵՐՈՒՄ ՏԵՂԵԿԱՏՎՈՒԹՅԱՆ ՓՈԽԱՆՑՄԱՆ ԿԱՆԱԼՆԵՐԻ ԴԻՆԱՄԻԿ ՓՈՓՈԽՈՒԹՅԱՆ ԱԼԳՈՐԻԹՄ ԵՎ ԴՐԱ ՏԵՂԸ ԳՈՅՈՒԹՅՈՒՆ ՈՒՆԵՑՈՂ ՄՈՏԵՑՈՒՄՆԵՐԻ ՇԱՐՔՈՒՄ**

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[1]Հայաստանի ազգային պոլիտեխնիկական համալսարան

[2]Երևանի կապի միջոցների ԳՀԻ

Առաջարկվում է ad-hoc IoT ցանցերում ցանցային կառուցվածքների դինամիկ փոփոխման առկա ալգորիթմների դասակարգում: Նկարագրված է տեղեկատվության փոխանցման կանալների դինամիկ փոփոխման առաջարկվող ալգորիթմը և գտնված է նրա տեղը առկա մոտեցումների շարքում:

Ալգորիթմը օգտագործում է Դեյկստրայի ամենակարճ ճանապարհի մեթոդը բազմակի գնահատման կշռայնացված ֆունկցիայով, որը ինտեգրում է հինգ կշռայնացված գործոնները՝ հանգույցի մնացորդային էներգիան, հանգույցների միջև հեռավորությունը, անլար կապի որակը, հանգույցի տրաֆիկի բեռնվածությունը և կապի խցանումը: SimPy և NetworkX հիման վրա Python լեզվով մշակված է դիսկրետ իրադարձությունների մոդելավորման շրջանակ՝ առաջարկվող ալգորիթմը գնահատելու համար չորս հաստատված երթուղավորման արձանագրությունների դեմ՝ ամենակարճ ճանապարհի (hop-count), AODV, LEACH-C և էներգիայի վրա հիմնված երթուղավորում: Ներկայացվում են իրականացված հետազոտության արդյունքները և դրանց համեմատական վերլուծությունը:

Համապարփակ փորձերը հինգ սցենարներով, որոնք ներառում են 30 անկախ փորձարկում 50 հանգույցով, ցույց են տալիս, որ առաջարկվող բազմագործոնային ալգորիթմը հասնում է փաթեթների առաքման ամենաբարձր հարաբերակցության՝ 98.9% անշարժ ցանցերում և 96.9% շարժական միջավայրերում՝ միաժամանակ պահպանելով մրցունակ առաքման ուշացում և էներգիայի կայուն սպառում: Մասշտաբայնության փորձարկումները մինչև 200 հանգույցով հաստատում են արտադրողականության կայուն առավելությունները: Ցույց է տրվում առաջարկվող ալգորիթմի օգտագործման առավելությունը ցանցային կառուցվածքի փոփոխման համար տարբեր չափանիշների համաձայն, ներառյալ փաթեթների առաքման հարաբերակցությունը, ցանցի կյանքի տևողությունը և էներգիայի սպառման մակարդակները: Քննարկվում են բոլոր փորձարկված ալգորիթմների ընդհանրությունները և ներկայացվում են աշխատանքի եզրակացությունները:

Բանալի բառեր: ad-hoc ցանցեր, դինամիկ տոպոլոգիայի կառավարում, բազմակի չափանիշների երթուղավորում, IoT mesh ցանցի մոդելավորում, էներգիայի վրա հիմնված երթուղավորում, Դեյկստրայի ալգորիթմ, անլար սենսորային ցանցեր, դիսկրետ իրադարձությունների մոդելավորում

АЛГОРИТМ ДИНАМИЧЕСКОГО ИЗМЕНЕНИЯ КАНАЛОВ ПЕРЕДАЧИ ИНФОРМАЦИИ В AD-HOC IOT СЕТЯХ И ЕГО МЕСТО СРЕДИ СУЩЕСТВУЮЩИХ ПОДХОДОВ

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Представлена классификация существующих алгоритмов динамического изменения сетевых структур в ad-hoc IoT сетях. Описан предлагаемый алгоритм динамического изменения каналов передачи информации и установлено его положение среди существующих подходов.

Алгоритм использует метод кратчайшего пути Дейкстры с композитной взвешенной функцией стоимости, интегрирующей пять взвешенных факторов: остаточную энергию узла, расстояние между узлами, качество беспроводной связи, загруженность узла трафиком и перегруженность канала. На основе SimPy и NetworkX разработана платформа дискретно-событийного моделирования на Python для оценки предлагаемого алгоритма по сравнению с четырьмя установленными протоколами маршрутизации: кратчайший путь (hop-count), AODV, LEACH-C и энергоэффективная маршрутизация. Представлены результаты проведенного исследования и их сравнительный анализ.

Комплексные эксперименты по пяти сценариям, включающие 30 независимых испытаний с 50 узлами, демонстрируют, что предлагаемый многокритериальный алгоритм достигает наивысшего коэффициента доставки пакетов 98,9% в стационарных сетях и 96,9% в мобильных средах, при этом сохраняя конкурентоспособную задержку и справедливость распределения энергии. Тесты масштабируемости с количеством узлов до 200 подтверждают устойчивые преимущества производительности. Продемонстрировано преимущество использования предлагаемого алгоритма для изменения структуры сети по различным критериям, включая коэффициент доставки пакетов, время жизни сети и справедливость распределения энергии. Обсуждаются общие черты всех протестированных алгоритмов и представлены выводы работы.

Ключевые слова: ad-hoc сети, управление динамической топологией, многокритериальная маршрутизация, моделирование IoT mesh сетей, энергоэффективная маршрутизация, алгоритм Дейкстры, беспроводные сенсорные сети, дискретно-событийное моделирование.

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TECHNOLOGY FOR GENERATING ARTIFICIAL WIND AND ITS APPLICATION IN ENERGY PRODUCTION

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Abstract

The diversity of forms of electrical energy use in virtually all areas of our society underscores the relevance of the concept of developing more powerful energy sources that cause minimal harm to the environment. Wind energy, which has undergone rapid development, has until recently been considered one of the most environmentally friendly ways to generate energy. However, as our knowledge of environmental issues has expanded, its numerous shortcomings have become apparent. The proposed technology not only allows artificial wind to be generated in any local area, but also uses turbine-type wind generators, which eliminate all the disadvantages of traditional wind generators. The article proposes a design for a wind power plant that implements this technology, considers issues related to its daily activity, and analyzes how its parameters depend on the seasons. A modification of the wind power plant is proposed for construction in foothill areas, where the highest power generation rates are achieved.

Key words: artificial wind generator, wind power plant, turbine-type wind generator, energy ecology.

Introduction

Growing public demand for the preservation of our planet's ecological purity is encouraging scientists to develop more powerful sources of renewable energy capable of replacing nuclear and thermal power plants, which cause the most damage to the environment. Not only do they produce high levels of harmful emissions, but each of them, with an efficiency of approximately 30-40%, releases the remaining energy from its production cycle into the atmosphere in the form of thermal energy, which is twice the amount of energy supplied to the homes of its actual consumers.

Hydropower is the cheapest and most environmentally friendly way to generate electricity. With capital investments in power plant construction amounting to only $1,400 per 1 kW of energy, it generates 14.7% of global energy consumption, according to the International Energy Agency's data for 2024. However, its further development does not seem possible, as all countries have already fully utilized their water resources since the construction of the first power plant in 1882 in the United States on the Fox River (740 W) and the next more powerful one (37 MW) built on Niagara Falls in 1895. From this perspective, global wind energy resources can be considered inexhaustible. Therefore, despite the rapid growth in the share of wind energy in global electricity consumption from 1.1% in 2001 to 8.1% in 2024, it seems appropriate to develop more technologically advanced methods of converting wind energy into electricity and to conduct a comparative analysis of their parameters with the traditional technologies currently in use.

Disadvantages of traditional energy production technologies

Coal-fired power plants cause the most damage to our planet's environment, emitting 900 g of various harmful substances into the atmosphere for every 1 kW*hour of energy produced, a large proportion of which is carbon dioxide, emissions of which amounted to 40 gigatons in 2023 alone. The emissions from coal-fired power plants also include toxic compounds of lead, thorium, uranium, and other heavy metals, which can accumulate in the human body. Coal-fired power generation ranks second after hydropower in terms of capital investment in power plant construction, at $2,000 per 1 kW of capacity. Therefore, it is regrettable to note that coal is currently the largest source of electricity, generating 34% of the world's energy [1], which is more than three times the share of nuclear power plants (10%), which emit only 28 g of harmful substances per 1 kW *hour of energy into the atmosphere. However, nuclear power plant reactors produce about 300 different radionuclides, 30 of which can enter the atmosphere, with half-lives ranging from several days to several years.

During its operation, a nuclear power plant does not directly emit carbon dioxide, however, the concept of a “carbon footprint” has been introduced for them, which includes the amount of carbon dioxide generated during uranium ore mining, uranium enrichment, and radioactive waste management, amounting to 88-146 g per 1 kW*hour of energy generated from this fuel [2]. The disadvantages of nuclear power plants include very high capital investments in their construction—$5,500 per 1 kW of capacity—and equally high costs for decommissioning. The Massachusetts Institute of Technology has calculated that the cost of decommissioning a nuclear power plant is 10-15% of the cost of its construction. However, experience shows that in some cases these costs can be many times higher. For example, in France, the cost of decommissioning the Brenilis nuclear power plant increased 20 times compared to the planned cost and amounted to €480 million. In the UK, 19 nuclear power plants are decommissioned each year, costing £3 billion in budget funds.

According to Climate News Network estimates, 48 of the 144 nuclear power plants operating in Europe should begin the decommissioning process as early as 2025. This is despite the fact that such advanced countries as Austria and Germany stopped building new nuclear power plants back in 2000. This was dictated not only by the noted shortcomings of nuclear power plants operating in normal mode, but also by the continuing threat of accidents with unpredictable consequences. On April 20, 1986, an explosion at the Chernobyl nuclear power plant released radioactive substances into the environment equivalent to 500 Hiroshima bombs. On March 11, 2011, despite strict compliance with operating rules, a 15-meter tsunami flooded the «Fukushima-1» nuclear power plant and caused three reactor core meltdowns. The process of gradually abandoning nuclear energy is influenced not so much by the high costs of construction and decommissioning, but primarily by the steady increase in its cost as our knowledge of environmental issues grows [3] and the requirements for the construction of nuclear safety systems and the process of storage and disposal of nuclear waste increase. At the same time, the cost of wind and solar energy is steadily decreasing as technology advances, and the share of solar energy production worldwide has doubled over the past three years, reaching 6.9% in 2024. One of the disadvantages of solar energy is its high capital investment—$4,000 per 1 kW of capacity, second only to nuclear energy. The efficiency of solar panels declines by about 1% per year, so the entire fleet of panels in solar power plants needs to be replaced every 25 years. According to the US National Renewable Energy Laboratory, recycling solar panels is not economically viable: recycling one panel costs $20-30, while only $2-4 worth of materials can be recovered for reuse. Therefore, only in some countries are up to 10% of panels recycled, while the majority are dumped in landfills, transferring toxic heavy metals such as cadmium, selenium, and lead there. According to estimates by the Foundation for Environmental Education (FEE), the amount of this waste will reach 160 million tons by 2050, which is four times the amount of waste from wind turbine blades.

The harm caused by the production of solar panels is also a major concern for scientists [4]. The process of obtaining silicon from silicon dioxide (silicon ore) is extremely energy-intensive, involving the preliminary processing of ore in special furnaces, which consume 40-60 MW*hour of energy per ton of silicon produced, which is supplied by coal-fired power plants to keep production costs low. In the process of producing this amount of energy, these power plants emit 200-400 tons of carbon dioxide into the atmosphere. Therefore, although solar panels do not emit harmful substances during their operation, the “carbon footprint” from their production is 170-250 g per 1 kW*hour of energy generated [5]. The production of solar panels is also characterized by toxic soil and water pollution. After being processed in a furnace, silicon is extracted from ore through a chemical reaction with sulfuric acid, resulting in 3-4 tons of silicon tetrachloride being released for every ton of silicon produced. In most countries, this is simply dumped into rivers, as its processing requires high costs and special equipment.

Disadvantages of traditional wind generators

Capital investments in the construction of wind power plants (Fig. 1) are almost two times lower than those for solar power plants and amount to $2,200 per 1 kW of capacity according to 2024 data. However, compared to solar panels, their installation and further operation are extremely complicated.

Fig. 1. Wind turbine design and their location on the site.

Due to the absence of harmful emissions into the atmosphere, wind energy has long been considered comparable to hydropower in terms of environmental friendliness. However, as various aspects of its interaction with the environment have been studied in greater detail, some very significant drawbacks have become apparent:

- Wind power plants generate infrasound with a frequency of about 20 Hz, which is very harmful to humans and cannot be combated by technical means, since it arises when the wind flow comes into contact with the blades and has a high penetrating ability, unlike sound vibrations.
- Infrasound scares away snakes, rodents, small predators, and birds, which leads to the proliferation of pests and makes the fields under wind turbines unsuitable for agriculture and animal husbandry.
- Wind turbine blades kill birds and bats. American scientists from the animal protection service have determined that wind turbines killed 440,000 birds in one year, and coastal wind turbines killed 200 bats in just six weeks.
- After the blades reach the end of their service life, the composite materials they contain prevent them from being used as secondary raw materials. Therefore, landfilling is the only way to dispose of them, which a number of European countries have already banned on their territory. Nevertheless, this problem adds to the global problem of plastic waste disposal, and by 2050, 40 million tons of spent blades will need to be disposed of somewhere [6].
- Moving wind farms to the sea is no less destructive to nature. In the absence of visible changes on the surface, the entire spectrum of vibrations generated by the turbine supports is transmitted to their base, dispersing sea creatures and traveling through the aquatic environment over considerable distances. Energy specialists and environmentalists do not draw any conclusions from the fact that only higher marine mammals, which have a system of echolocation and sound communication between individuals, are washed ashore «for unexplained reasons».

It is very interesting to compare the characteristics of wind and hydroelectric power plants. In the latter, a dam on the river acts as a reservoir, directing the entire flow of river water into the turbines, transferring all its energy to them. This is not the case with wind generators—direct measurements on their design drawing (Fig. 1) show that only 5% of the wind passing through its overall size (red line) comes into contact with the wind generator blades. Taking into account international standards requiring a safe mutual arrangement of wind turbines at a distance of at least 5 diameters of the wind wheel, it turns out that a group of wind turbines converts only 1% of the energy of the wind blowing on them into electricity. In this regard, it should also be noted that before installing wind turbines in a particular area, each country conducts measurements of the wind speed and its seasonal stability necessary for the operation of wind turbines over a period of 2-3 years. Of course, these studies do not always yield positive results.

Artificial wind generation technology.

The noted shortcomings of traditional wind turbines are completely eliminated in the design of the wind power plant [7], which uses “artificial wind” technology. This technology allows an artificial difference in atmospheric pressure to be created on both sides of a wall facing south at any local site, and the wind generated by the pressure difference to be directed into turbine-type wind generators (Fig. 2) located at the base of the wall. This technology is based on a very interesting physical phenomenon that manifests itself in hurricane-force winds at the base of tall buildings, caused by the large pressure difference between the facade of the building, which is strongly heated by the sun, and the low temperature in the shaded area on its north side [8]. Such winds, artificially generated in urban conditions, blow along the streets adjacent to the building, knocking pedestrians and cyclists off their feet [9,10]. The technology for reducing the intensity of these winds [11,12], which analyzes the process of their formation around skyscrapers with south-facing facades, proposes installing pipes running from north to south on the technical floors of such buildings, which will provide the wind with a shortened corridor through the building (Fig. 3) and reduce its speed on the streets. The pipes enter the building from the area of highest atmospheric pressure at the very base of the northern wall of the skyscraper and exit from the south at the level of the second floor so as not to interfere with pedestrians and traffic. At the same time, the air flow in the pipes is quite powerful—the wind at the pipe outlets has a speed of 20-30 m/s and is ejected up to a distance of 40 m [8].

The installation of generators in pipes is an obvious consequence of this technology, bringing it into the field of energy. To preliminarily assess the potential of this method for energy generation, the results of computer modeling of the process of solar heating of the aluminum-clad Bridgewater Place skyscraper on June 22 (Fig. 4) and December 22 [8].

The calculated values of the temperature difference between the building facade and its shaded area, which forms wind in the pipes, reach 50^0C in summer and 60^0C in winter, which allows the classic theory of a «thermodynamic machine» to be used for the case of a minimum temperature difference. The efficiency in this case will be $Q = 50^0K / 300^0K = 1/6$, where 300^0K is the average temperature of the system. The initial energy of the entire system is determined based on the energy of solar radiation falling on 1 square meter of surface area - 0.6 kW. For the Bridgewater Place skyscraper, with a height of 112 m and a width of

80 m, the total energy is 5,376 kW, which, taking into account the efficiency Q = 1/6, gives a resulting power E = 896 kW.

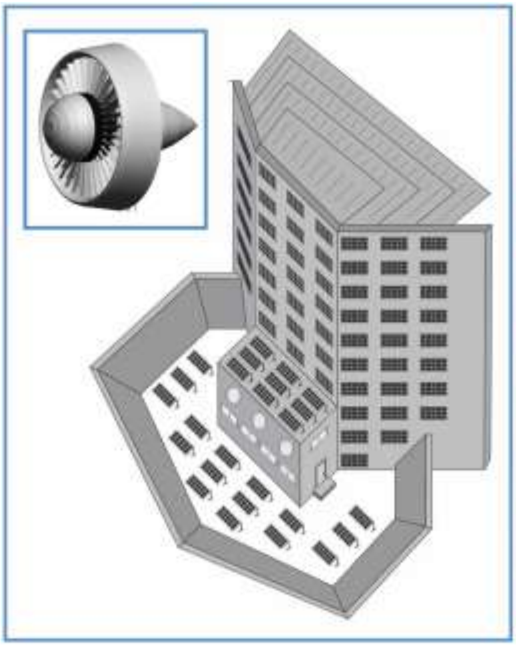


Fig. 2. Wind farm and turbine-type wind generator.

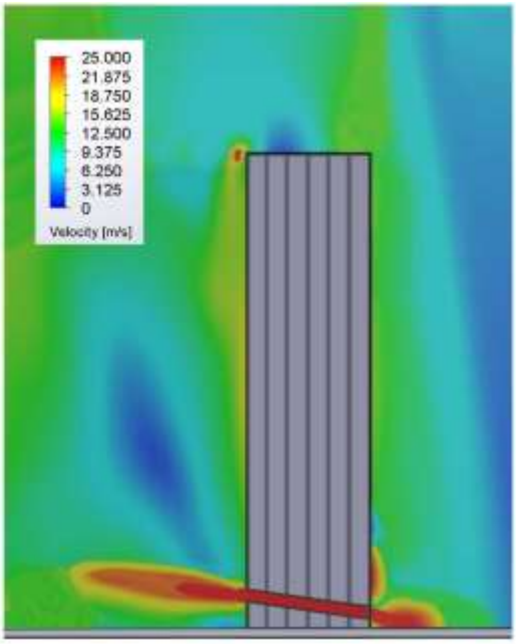


Fig. 3. Technology for reducing wind speed at the base of a skyscraper.

A more accurate assessment, taking into account the physical aspect of the phenomenon, is provided by examining a computer model of the upward air flow on the facade of the Bridgewater Place skyscraper (Fig. 5), formed when it was heated to 73^0C on June 22 (Fig. 4). This air flow moves at a speed of 11.1 m/s and carries a volume of air of 10,983.7 m^3/s. As this volume moves upward, the same volume of air is drawn in through the pipes, for which the mass can be calculated taking into account the air density of 1.225 kg/m^3 and the kinetic energy E = 833 kW. These two practically identical estimates show that an aluminum-clad surface area of approximately 10,000 square meters can generate enough energy to power 600 apartments (according to European standards - 1.4 kW per apartment) [13,14].

The design of the power plant (Fig. 2) is intended for industrial implementation of the noted physical phenomenon and amplification of factors influencing the process of artificial wind formation through the use of additional technical means.

To this end, the entire territory of the power plant is divided into northern and southern sections by a wall, the surface of which, together with the adjacent southern section, is covered with heat-absorbing shields to form the strongest possible upward flow when heated by the sun. Special materials such as technically pure aluminum - AD1(1050) or stainless steel - AISI304, which have a higher thermal conductivity and solar radiation absorption coefficient than the decorative aluminum sheet used to clad the Bridgewater Place skyscraper, which heats up to 73^0C on June 22. The maximum heating temperature can be achieved with the help of special selective paint used in solar collectors - Thurmalox 250 and selective coating based on titanium oxynitrate - Tinox, which significantly reduce the surface heat radiation coefficient and create a “heat trap” effect in the collector design. Solar panels, which heat up to only 60^{0}C in the sun, can also be used as heat-absorbing shields, but in this case, the power plant will operate in hybrid mode and make full use of all its surfaces.

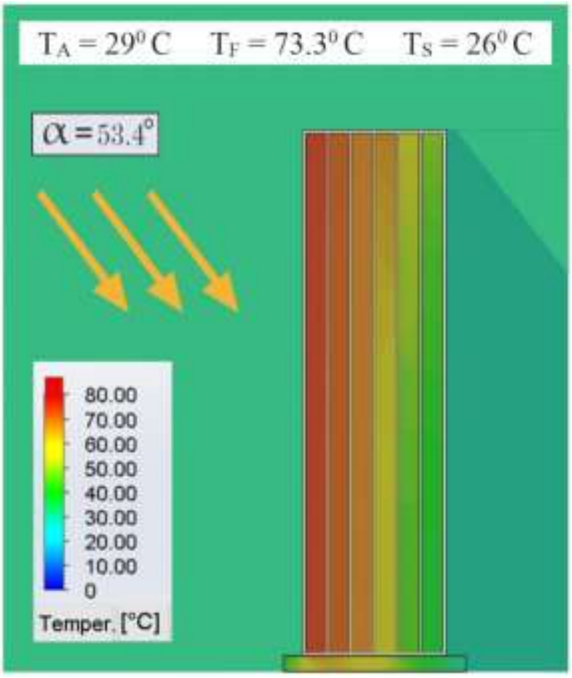


Fig. 4. Simulation of solar heating of the Bridgewater Place skyscraper on June 22.

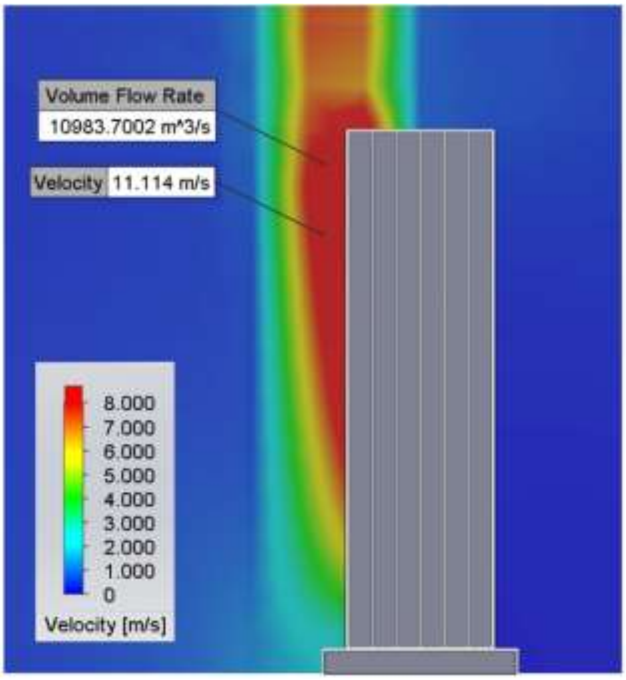


Fig. 5. Computer model of the updraft on the facade of the Bridgewater Place skyscraper.

A very important design element is the fence around the southern section of the power plant, which prevents ambient air from being drawn into the low-pressure area at the base of the wall formed by the upward flow. In this case, all the air compensating for this pressure drop will be drawn in through the pipes on the northern side of the power plant. This will be facilitated by the location of the fence above the level of the pipe outlets, which, for the safety of personnel, are located at the level of the second floor of the control building. The walls of the fence should be tilted outward from the station territory at an acute angle so as not to shade the sun from the heating shields. Special measures have also been taken in the design of the power plant to maintain cold night temperatures in its northern section for as long as possible. To achieve this, side barriers have been built on both sides of the central wall to prevent sunlight from entering this area even at sunrise and sunset, and the common roof has a stepped structure that allows snow to be thrown off it onto the ground and ensures long-term cooling. The roof supports must be made of massive reinforced concrete structures and arranged in a checkerboard pattern to ensure sufficient contact with the air drawn into the area for maximum cooling.

For computer modeling of the wind power plant operation process, its design (Fig. 2) is represented by the following dimensions: vertical wall surface area - 100 x 100 m, northern and southern areas - 100 x 100 m. The computer model of this structure (Fig. 6) is represented by hot (red) and cold (blue) areas separated by a wall with 10 holes, each 9.8 m in diameter. The process of heating this structure by the sun is calculated for the coordinates of Marseille (southern tip of Europe, France) at two extreme points of solar activity - June 22 and December 22, provided that the entire surface of the vertical wall and the southern horizontal section of the power plant are clad with 3 mm metal with a thermal conductivity coefficient of 150 W/m*K (with a maximum of 230 W/m*K for pure aluminum), a solar energy absorption coefficient of 0.96 (with a maximum of 0.99 for Black Chrome) and a thermal radiation coefficient of 0.52 (with a minimum of 0.04 for Tinox coating). The simulation was performed using the “Flow Simulation 2024 SP2.0.Build: 6320” version of the SOLIDWORKS computer program, taking into account the ambient air temperature T_A by hour and season of the year in accordance with data from the French National Meteorological Service (MFI) [15].

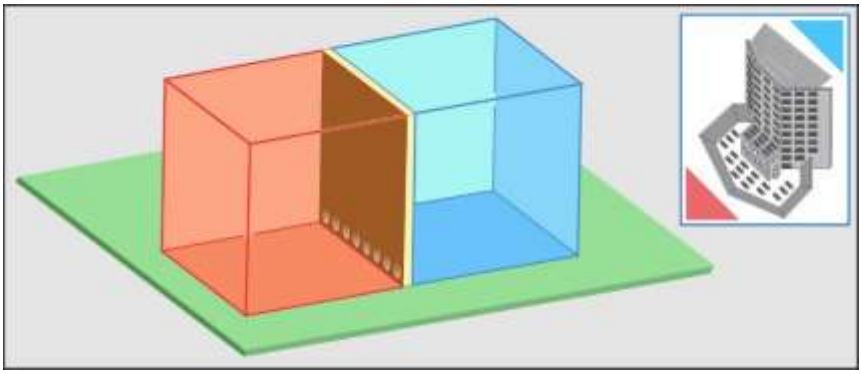


Fig. 6. Computer model of a wind power plant.

The results of computer modeling show that the vertical and horizontal surfaces of the model in Fig. 6 are heated to the maximum on June 22 when the sun reaches its zenith and form thermal zones (Fig. 7) with temperatures in the center $T_V = 108.6\ ^0C$ and $T_H = 135.2\ ^0C$, respectively. Each of the marked thermal zones forms an upward air flow (Fig. 8), which, when moving upward, draws in volumes of air P_V and P_H (Tab.1) through the pipes, generating power E_V and E_H in the pipes. The analysis does not take into account the factors of additional heating of the marked surfaces due to their mutual influence, however, the result of simply summing the E_0 calculated values of the power they generate shows that equipping a vertical wall the size of the Bridgewater Place skyscraper with special technical means that enhance the process of artificial wind formation allows the amount of energy generated to be increased from 0.8 MW to 4-7 MW. Such a power plant can be built in any chosen location, regardless of its wind rose, in close proximity to any populated area and provide electricity to 4,000 apartments. Taking into account the global solar irradiance constant (1361 W/m²), the power plant’s efficiency under the optimal conditions described above will be 25.7%.

The data in Tab.1 show an interesting pattern: in winter, when the vertical wall is relatively cool, it generates more power than in summer due to the large difference between its temperature and the temperature of the northern part of the power plant. This pattern also applies to the heating of the horizontal surface of the power plant, increasing the level of energy generated in winter, but this is not reflected in its excess over the level of energy in summer due to the very low heating temperature of the horizontal surface in winter, caused by the low angle of the sun above the horizon (December 22, Marseille, zenith - 23.27^0) and the position of its rays practically tangential to the surface. It should be noted that such a low position of the sun in winter is preferable for heating a vertical wall—the sun's rays fall on it almost perpendicularly, so even at low ambient temperatures, it heats up only 25% less than in summer and generates 25**%** more energy due to the temperature difference mentioned above. From this perspective, it can be stated that the operating cycles of vertical and horizontal surfaces complement each other, which allows for smoothing out seasonal fluctuations in the total generated power E_0.

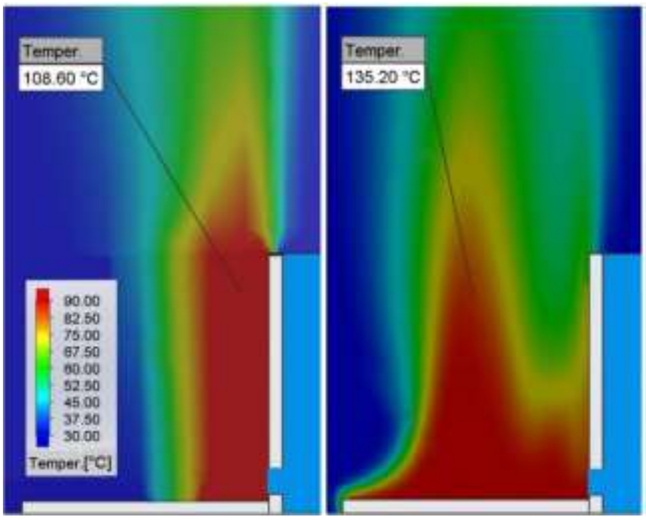


Fig. 7. Thermal zones of the vertical and horizontal surfaces of a wind power plant.

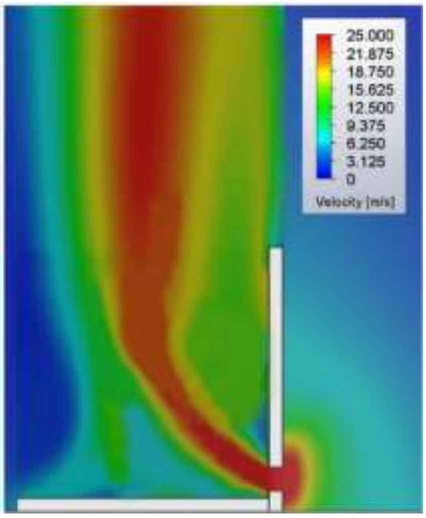


Fig. 8. Upward flow of a wind power plant.

Tabле 1

Wind farm parameters on June 22 and December 22 (sun at its zenith)

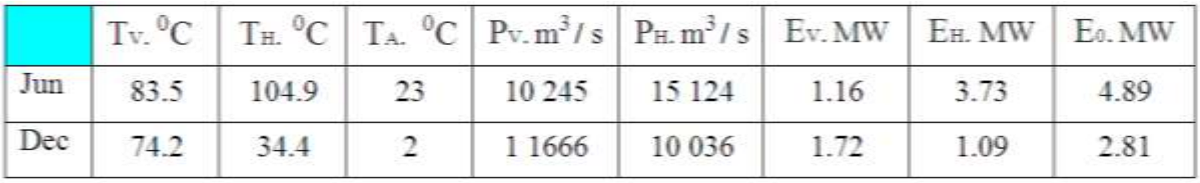
	T_V. ^{0}C	T_H. ^{0}C	T_A. ^{0}C	P_V. m^3/ s	P_H. m^3/ s	E_V. MW	E_H. MW	E_0. MW
Jun	108.6	135.2	32	12 058	16 878	1.89	5.18	7.07
Dec	96.3	53.1	10	12 983	11 924	2.36	1.83	4.19

Operating exclusively within the framework of solar energy conversion, wind power plants are characterized by a longer daily activity cycle than solar panels, due to the presence of elements with thermal inertia in their design, which maintain the temperature regime for some time after sunset in both the cold and heated areas of the power plant. The thermal inertia of the entire structure can be significantly increased through the use of special technologies for storing solar heat and accumulating cold during the night, using liquid elements of solar collectors that can be built into the walls and foundations of both areas of the power plant. The use of these technologies can ensure continuous energy generation, and the analysis of its daily fluctuations should be combined with an assessment of the costs of creating a thermal inertia system. Such an analysis should also be based on a compromise choice of the volumes of use of well-known energy conversion and storage technologies, which are an integral part of solar power plants and traditional wind turbines.

To assess the daily activity of a wind power plant without taking thermal inertia into account, computer modeling of its operation was performed at 9 a.m. on June 22 and December 22. Calculations of the sun's movement along the ecliptic [8] show that in both summer and winter, by 9 a.m. it has already risen more than halfway to its daily maximum and provides an average of up to 70**%** of the maximum energy produced by vertical and horizontal surfaces in each season (Tab.2).

Tabле 2

Wind farm parameters on June 22 and December 22 (9:00 a.m.).



	$T_{V.}\ ^0C$	$T_{H.}\ ^0C$	$T_{A.}\ ^0C$	$P_{V.}\ m^3/s$	$P_{H.}\ m^3/s$	$E_{V.}$ MW	$E_{H.}$ MW	$E_{0.}$ MW
Jun	83.5	104.9	23	10 245	15 124	1.16	3.73	4.89
Dec	74.2	34.4	2	1 1666	10 036	1.72	1.09	2.81

This allows us to conclude that during daylight hours, fluctuations in the level of energy generated do not exceed 30**%** and can be stabilized at 80-85**%** of the maximum using energy storage and stabilization technology. The power plant's operation was simulated only from dawn to zenith because, in terms of solar radiation intensity, all processes are mirrored until sunset, and a special methodology needs to be developed to study the impact of thermal inertia processes occurring after the sun passes the zenith on the power plant's parameters [8].

For the construction of wind power plants generating higher capacities, heat-absorbing shields with higher "thermal" characteristics than those used in the calculations can be used. For comparison, it should be noted that if the above-mentioned higher characteristics of heat-absorbing material are used in the simulation, which showed a result of heating the horizontal surface to 135.2 ^{0}C, the surface temperature will increase to 198.4 ^{0}C. A further increase in power can only be achieved by increasing the surfaces that generate upward flows in the power plant. It should be noted that, according to the results of computer modeling, the upward flow from the horizontal surface contributes the most to the total energy. Consequently, increasing the size of this surface is preferable when constructing power plants.

Operational advantages of wind power plants

The high energy performance of wind power plants is complemented by a number of operational advantages due to the concentration of their entire output power in a narrow section of pipes, which makes it possible to install turbine-type wind generators in them. This primarily leads to a sharp reduction in the size of the wind wheel compared to traditional wind turbines, which must have a diameter of 35 m to generate 1 MW of power, while the world's most powerful wind turbine, the Enercon E-126, manufactured in Germany since 2012, has a diameter of 126 m and a total weight of 6,000 tons. With a capacity of 7.58 MW, comparable to that of a wind power plant (Tab.1), it is designed to supply power to 5,000 apartments (1.5 kW each) [14], but has not found application due to its high price of $14 million.

The use of turbine-type wind generators in power plants makes energy generation very technologically advanced—generator maintenance is carried out directly in the power plant building, rather than at a height of 100 meters or more. The all-metal construction of the turbine generator is easy to repair and can be recycled without loss at the end of its service life. Operating in the high wind speed range, turbine generators are characterized by high speeds, which eliminates the formation of infrasound harmful to humans and converts vibrations into the sound range with noise levels of 30-40 decibels, with an acceptable level of 45 decibels for residential and office premises and 55 decibels for factory premises. This allows wind farms to be built near residential buildings and ensures the safety of maintenance personnel. The design of these generators allows for external sound insulation and the installation of protective grilles, making them safe for humans and animals.

Turbines with a diameter of up to 6 m are manufactured at some European universities for installation on the roofs of their buildings and are estimated to cost $2,000. At the same time, steam turbines were characterized by a more complex design when they were first used in 1899 at a coal-fired power plant in Elberfeld (Germany), where a 15-stage steam expansion method was used in a turbine with a diameter of 2 m. Currently, turbines with a diameter of up to 4 m are being produced at a cost of $400 million per 1 GW of capacity. A similar calculation based on Tab.1 shows that wind turbines cost $5.5 million per 1 GW of capacity, which is incomparably lower.

This comparison allows us to estimate the capital investment required to build a wind power plant, assuming that a nuclear power plant of the same capacity has the same low-cost turbine and the same cost of housings, which together correspond to the total cost of the wind power plant shown in Fig. 2 and are denoted by A. In this case, the cost of the reactor, the first and second steam generation circuits, the condenser, and the cooling towers is added to this cost for the nuclear power plant, which is denoted by 2A, as well as the cost of the radiation protection complex, which accounts for 40% of the total cost of the nuclear power plant. Therefore, its total cost can be represented by the equation $B = A + 2A + 0.4B$, which is converted to the form $B = 5A$. Thus, capital investments in the construction of a wind power plant amount to $1,100 per 1 kW of capacity, which is lower than the cost of constructing hydroelectric power plants with the same indicators of absolute environmental safety.

Wind power plant in the foothills

The capacity of the wind power plant shown in Fig. 2 can be significantly increased if the cold air from the northern part of the plant is replaced with air from the mountain range [16], which is drawn from the area of highest atmospheric pressure at its base through pipes laid under the foothills and fed directly to the south-facing wall of the power plant with turbines located in it (Fig. 9). For the construction of such a power plant, it is advisable to choose a location that includes foothills (Fig. 10), which serve as a barrier to the wind blowing from the mountains into the valley and form the above-mentioned area of high pressure at the base of the mountain range.

Pipes leading into this area provide cold air with a shortened corridor into the sun-warmed valley and the power plant area, which is heated by additional technical means. The location of the pipes at a considerable distance from each other helps to ensure that the areas of air intake do not overlap and weaken each other. The wind formed in the pipes will help reduce pressure at the base of the mountain range, causing new flows of cold air blowing from the mountains to descend there, which will be completely drawn into the pipes and fed to the wind turbines of the power plant. The above description of how a foothill wind power plant works shows that it is significantly more productive than traditional wind turbines installed on foothill elevations (Fig. 1), whose blades capture only 1% of the wind blowing from the mountains.

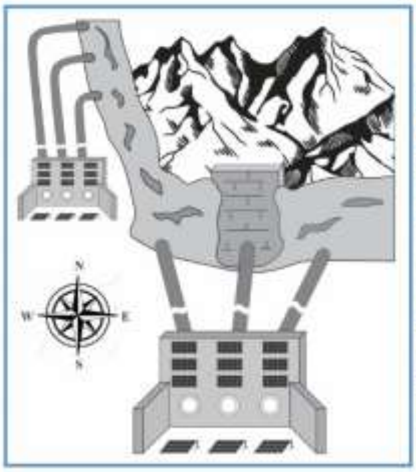


Fig. 9. Foothill wind power plant.

Fig. 10. Foothills in the Alps.

To build such a power plant, it is preferable to locate it south of the mountain range in accordance with the requirement that the central wall of the power plant face south for maximum heating by the sun. However, the power plant can also be built on any section of the mountain range (Fig. 9), in which case the pipes can be given a smooth bend to maintain the southward orientation of the entire power plant structure. The features of the landscape may allow the pipes to be led into the valley through natural passages between the foothills, which, after the pipes have been laid, are built up with a wall (Fig. 9) that serves as the same barrier to mountain air as the foothills. This technique allows mountainous terrain without foothills to be used for the construction of a power plant. In this case, the dimensions of the wall must be significantly expanded so that it can function as a dam in the above example with a hydroelectric power plant. For a preliminary assessment of the technical characteristics of the proposed energy generation method, it is interesting to compare it with the “Atmospheric Power Plant” [17], developed by the American company "Cold Energy" in 2004.The company's scientists calculated that between geographical points 300 km apart, an atmospheric pressure difference of 0.03 atmospheres (22.8 mm Hg) is formed. If three pipes with a diameter of 2.5 m are laid between these points, a supersonic wind will form in them, which will allow generating up to 1 GW of power at a cost of 0.1-1 cent per 1 kW* hour. The project was not implemented due to the long length of the pipes passing through several states [18]. The proposed power plant allows the high technical characteristics of the noted project to be realized by using the atmospheric pressure difference between such diametrically opposed climatic zones as a snow-covered mountain range and a residential area in a sun-warmed valley (Fig. 10), which are located in close proximity to each other and separated by foothills. With temperatures in the Alps ranging from -10 to -15 ^{0}C and daytime temperatures “in the sun” ranging from 33 to 38 ^{0}C, according to data from the MFI in Marseille, located at the southwestern tip of the Alps, there is a temperature difference of approximately 50 ^{0}C and an atmospheric pressure difference of 14 mm Hg between them (0.28 mm Hg for every 1 ^{0}C). This is even without taking into account the humidity of the mountain air and special measures for additional heating of the southern section of the power plant (Fig. 9). At the same time, a wind flow with a speed of 174.6 m/s is formed in a single pipe with a diameter of 10 m and a length of 100 m, which generates 250.1 MW of power [19]. When the diameter of the pipe is reduced to 6 m for the installation of the above-mentioned 6-meter turbine-type wind turbines manufactured in European universities, the power generation decreases to 41.9 MW, which is nevertheless sufficient to supply electricity to a city with a population of approximately 120,000 people. The calculations assume that, to reduce the internal resistance of the pipes, special «epoxy smooth coatings» – such as the widely used brands «Amercoat» and «Scuthkote», which have a friction coefficient of 0.01– have been applied, as is common practice in gas pipeline technology.

The capacity of such a power plant can be increased by heating its territory with heat-absorbing shields, which, according to Tab.1 and Tab.2, will increase the temperature difference by an average of 50 ^{0}C even in winter, since the temperature in the mountains also drops at this time. When a temperature difference of 100 ^{0}C (28 mm Hg) is reached at the ends of a 6-meter pipe 100 m long, the wind speed in it will be 191.2 m/s and the power generation will reach 118.5 MW. Under the same conditions, a wind speed of 246.9 m/s will be generated in a 10-meter pipe, and the power will be 708.9 MW. The above assessment of the power of some options for implementing the principle of a foothill wind power plant highlights the prospects for the development of this method of energy generation and provides an opportunity to combine the efforts of many scientists, both from the energy sector and from related fields of science, to create a unified theory for the construction of such power plants and to develop methods for testing their parameters. In particular, it follows from the above that such power plants can contain either one pipe or several pipes connected to a common control point (Fig. 9). In the latter case, only the central pipe operates optimally, while the length of the side pipes increases significantly, leading to energy losses and requiring a compromise solution. For example, if the side pipes are directed at an angle of 45^0 to the central pipe, they become 1.4 times longer, which leads to a 20**%** power loss in each of them. In this case, it may be more expedient to build a separate control point for each pipe, located in a straight line towards the mountain range. In this case, the object of further research will be the optimal choice of the distance between power plants, which excludes mutual overlap of the areas of air flows drawn into their pipes. To evaluate this factor, calculations were performed on a computer model of a foothill wind power plant (Fig. 11), which includes the heated section of the power plant model shown in Fig. 6, connected by pipes to a segment of the mountain range, the walls of which, according to the program conditions, are closed to external air access from all sides except the top.

The results of calculations performed with a gradual increase in the size of the mountain massif segment show that the increasing power generated slows down the growth dynamics many times over at a level of about 1.5 GW with a mountain massif segment size of 3x3x3 km. This leads to the conclusion that the cold air resource contained in this segment allows the specified power to be generated without drawing in additional air masses from areas outside the segment, where neighboring power plants can operate at full capacity. The above calculations also allow us to make a first approximation of the cold air resources of the Alps - with a ridge length of 1,200 km and a width of 260 km, their area is 312,000 square kilometers, which accommodates 34,667 segments used in the calculations, each with a resource of 1.5 GW. Consequently, the energy resource of cold air in the Alps is 52,000 GW. This assessment does not take into account a number of natural factors that require narrow specialization. Due to the fact that the intake of heavy cold air into pipes from the upper layers of the atmosphere occurs not only in computer models but also in real nature, it is necessary to take into account the “vertical temperature gradient” (VTG), according to which the air temperature decreases by 5-6 ^{0}C for every 1,000 m of elevation.

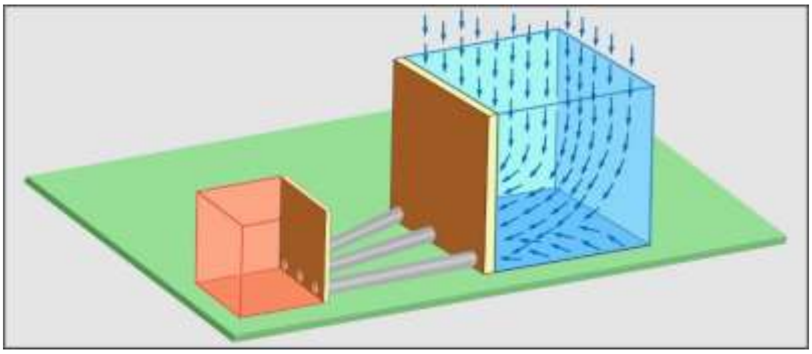


Fig. 11. Computer model of a foothill wind power plant and air movement in a mountain range segment

Therefore, in calculations with a temperature at the base of the mountain range equal to -10 ^{0}C, a correction must be made for the colder air coming from both the mountain peaks of the Alps with an average height of 2.5 km and the nearby heights of Mont Blanc (4,810 m) - the highest peak in the Alps, located on the border between France and Italy.

Conclusion

The proposed artificial wind generation technology provides an opportunity to develop a new generation of wind power plants, whose performance does not depend on the “wind rose” of the area and is determined only by the size and thermal characteristics of the sun-heated power plant structures. A south-facing vertical wall measuring 100x100 m and the adjacent area of the same size at the extreme points of solar activity on June 22 and December 22 generates 4-7 MW of power at noon with daily activity fluctuations of 30%, calculated for 9:00 a.m. The use of well-known technologies makes it possible to increase the thermal inertia of the power plant's structure and ensure round-the-clock energy generation, the parameters of which require the development of a special methodology for diagnosis. The construction of a wind power plant in the foothills allows the limited volume of air in its shadow area to be replaced by a significantly larger volume of colder air from the mountain range, which makes it possible to generate up to 1.5 GW of power and place power plants 3 km apart.

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ԱՐՀԵՍՏԱԿԱՆ ՔԱՄՈՒ ԳԵՆԵՐԱՑՄԱՆ ՏԵԽՆՈԼՈԳԻԱ ԵՎ ՆՐԱ ԿԻՐԱՌՈՒՄԸ ԷՆԵՐԳԵՏԻԿԱՅՈՒՄ

Մ. Վ. Մարկոսյան, Հ. Հ. Այվազյան

Երևանի կապի միջոցների ԳՀԻ

Էլեկտրական էներգիայի օգտագործման եղանակների բազմազանությունը ընդգծում է առավել հզոր էներգիայի աղբյուրների նախագծման կարևորությունը, որոնք բնութագրվում են նվազագույն ազդեցությամբ շրջակա միջավայրի վրա: Արագ զարգացում ստացած հողմային էներգետիկան մինչև վերջին տարիները համարվում էր առավել էկոլոգիապես մաքուր տեխնոլոգիաներից մեկը: Սակայն շրջակա միջավայրի խնդիրների մասին մեր գիտելիքների ընդլայնումը ի հայտ բերեց այդ տեխնոլոգիայի բազմաթիվ թերությունները: Առաջարկվող տեխնոլոգիան ոչ միայն թույլ է տալիս գեներացնել արհեստական քամին ցանկացած տարածքում, այլ և օգտագործում է իր աշխատանքային սկզբունքում տուրբինային տիպի հողմագեներատորներ, որոնք թույլ են տալիս հաղթահարել ավանդական հողմագեներատորների բոլոր թերությունները: Հոդվածում առաջարկված է հողմային էլեկտրական, որը իրագործում է նշված տեխնոլոգիան, դիտարկված է նրա չափանիշների կայունության գործոնները օրվա և տարվա կտրվածքով: Հողմային էլեկտրակայանի նախալեռնային տարածքում կառուցման տարբերակը թույլ կտա գեներացնել առավել բարձր հզորություն:

Բանալի բառեր ՝ արհեստական քամու գեներատոր, հողմային էլեկտրակայան, տուրբինային տիպի հողմագեներատոր:

ТЕХНОЛОГИЯ ГЕНЕРАЦИИ ИСКУССТВЕННОГО ВЕТРА И ЕЁ ПРИМЕНЕНИЕ В ЭНЕРГЕТИКЕ

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Многообразие форм использования электрической энергии практически во всех сферах жизнедеятельности нашего общества подчёркивает актуальность концепции разработки более мощных источников энергии, характеризующихся минимальным вредом для окружающей среды. Получившая бурное развитие ветровая энергетика до последнего времени считалась одной из наиболее экологичных способов генерации энергии. Однако, расширение наших знаний о проблемах экологии выявило её многочисленные недостатки. Предложенная технология не только позволяет генерировать искусственный ветер на произвольно взятом локальном участке, но и использует в своей основе ветрогенераторы турбинного типа, устраняющие все недостатки традиционных ветрогенераторов. В статье предложена конструкция ветровой электростанции, реализующей отмеченную технологию, рассмотрены вопросы её суточной активности, проведён анализ зависимости её параметров от сезонов года. Предложена модификация ветровой электростанции для случая строительства её в предгорной местности, при которой достигаются наибольшие показатели генерируемой мощности.

Ключевые слова: генератор искусственного ветра, ветровая электростанция, ветрогенератор турбинного типа.

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OPTIMIZATION OF THE HYDROLOGICAL POTENTIAL OF THE REGION
IN ORDER TO OVERCOME THE SHORTAGE OF DRINKING WATER
IN THE VILLAGES OF THE ARTIK COMMUNITY OF THE REPUBLIC OF ARMENIA

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OPTIMIZATION OF THE HYDROLOGICAL POTENTIAL OF THE REGION IN ORDER TO OVERCOME THE SHORTAGE OF DRINKING WATER IN THE VILLAGES OF THE ARTIK COMMUNITY OF THE REPUBLIC OF ARMENIA

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Abstract

Ensuring reliable access to safe drinking water remains a critical challenge in rural mountainous areas, where hydrological variability and infrastructure limitations lead to persistent water shortages. This study presents a comprehensive assessment of drinking water shortages in the Artik community (Armenia), where the total annual drinking water demand reaches 1.45 million m³, while the existing water supply covers only 50–55%, resulting in a deficit exceeding 1.03 million m³/year. Hydrological analysis reveals a small but dynamic basin ($F \approx 6.3$ km²) in the neighboring region (Tsakhkahovit community). The study demonstrates that the construction of a 500,000-square-meter reservoir represents a multifunctional solution that ensures a reliable drinking water supply and facilitates irrigation development in both communities.

Keywords: water scarcity; reservoir design; hydrological variability; drinking water supply

Introduction

In recent decades, global water resources have exhibited a clear declining trend due to the combined effects of climate change, population growth, and increasing water demand [10, 11, 12]. Hydrological systems worldwide are increasingly affected by altered precipitation regimes, reduced snowpack accumulation, and higher evapotranspiration rates, resulting in decreased surface runoff and groundwater recharge [27]. Recent global assessments indicate that nearly four billion people experience severe water scarcity for at least part of the year, highlighting the scale and urgency of the issue [21]. Water scarcity is further exacerbated by inefficient water management practices and growing competition among sectors, particularly in agriculture-dominated regions [13, 14]. The concept of water security has therefore become central to sustainable development, linking water availability with economic growth, environmental sustainability, and human well-being [22].

In mountainous regions, climate-induced changes are particularly critical due to their dependence on snowmelt and seasonal runoff patterns [28]. The increasing variability of hydrological regimes leads to higher frequency of both floods and droughts, complicating water resource planning and infrastructure design [23].

In Armenia, similar trends are observed, especially in highland and semi-arid zones, where water availability is strongly influenced by seasonal and climatic variability. Despite relatively sufficient national water resources, local imbalances result in significant supply deficits at the community level [18, 25]. These conditions emphasize the need for integrated water resource management approaches, including storage infrastructure such as reservoirs, to mitigate temporal and spatial mismatches between water availability and demand [16, 24].

Water scarcity is increasingly recognized as a multidimensional determinant of human health, extending beyond physical water availability to encompass access, reliability, quality, and affordability. Contemporary research distinguishes between physical water scarcity (limited natural availability) and economic water scarcity (insufficient infrastructure and governance), both of which contribute to adverse health outcomes. These dimensions collectively define household water insecurity, a concept that has gained prominence in recent interdisciplinary literature.

The health implications of water scarcity operate through interconnected pathways, including inadequate drinking water, compromised hygiene practices, reduced food security, and psychosocial stress. A recent systematic review and meta-analysis by Kimutai et al. (2023) demonstrated that water insecurity is significantly associated with poor mental health outcomes across diverse geographical contexts, highlighting its role as a global public health concern [1, 2].

One of the most direct consequences of water scarcity is the increased prevalence of waterborne and hygiene-related diseases. Limited access to safe drinking water and sanitation services facilitates the transmission of pathogens responsible for diarrheal diseases, cholera, and other gastrointestinal infections.

Empirical evidence consistently supports this relationship. For instance, Omotayo et al. (2021) found that access to clean water, improved sanitation, and adequate hygiene significantly reduces the incidence of diarrhea among children under five in South Africa [3]. Globally, inadequate water, sanitation, and hygiene (WASH) conditions are responsible for hundreds of thousands of preventable deaths annually, particularly among vulnerable populations such as children and the elderly.

Water scarcity directly affects public health by increasing the prevalence of waterborne diseases. Limited access to safe drinking water and sanitation services facilitates pathogen transmission, particularly in vulnerable populations (Fig. 1).

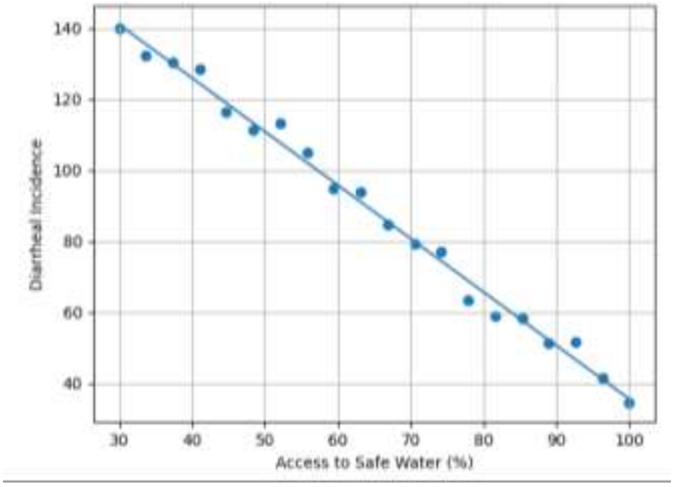


Fig. 1 **Relationship between access to safe drinking water and diarrheal incidence (regression-based analysis)**

As shown in Fig. 1, there is a strong inverse relationship between access to safe water and diarrheal incidence. The regression trend confirms that even moderate improvements in water access can significantly reduce disease burden.

Furthermore, drought conditions exacerbate these risks by reducing water quantity and quality simultaneously. Stanke et al. (2013) identified strong evidence linking drought to increased infectious disease transmission, especially in low-income and climate-vulnerable regions [4].

Water scarcity also exerts significant indirect effects on human health through its influence on food systems and nutritional outcomes. Reduced water availability limits agricultural productivity, decreases dietary diversity, and constrains food preparation practices.

Choudhary et al. (2021) demonstrated that household water insecurity is strongly associated with child undernutrition in India, with effects mediated not only by WASH-related pathways but also by reduced dietary diversity and food preparation constraints [5]. Water scarcity also indirectly affects human health through its impact on nutrition and food systems (Fig. 2).

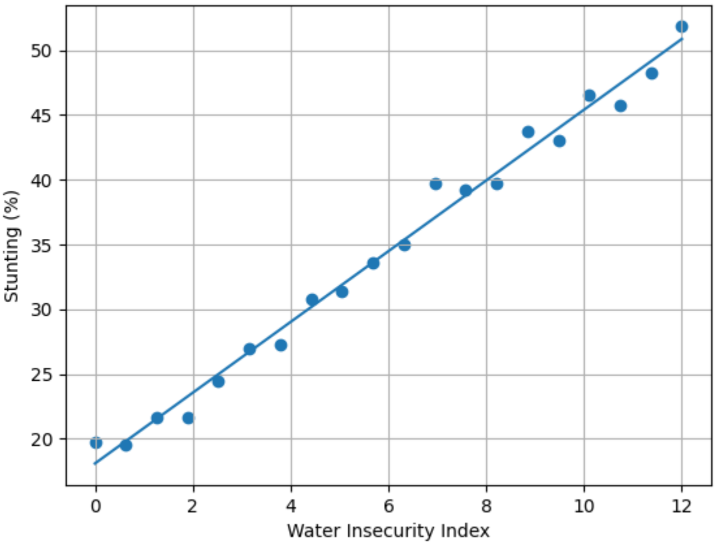


Fig. 2 Association between household water insecurity and child stunting prevalence

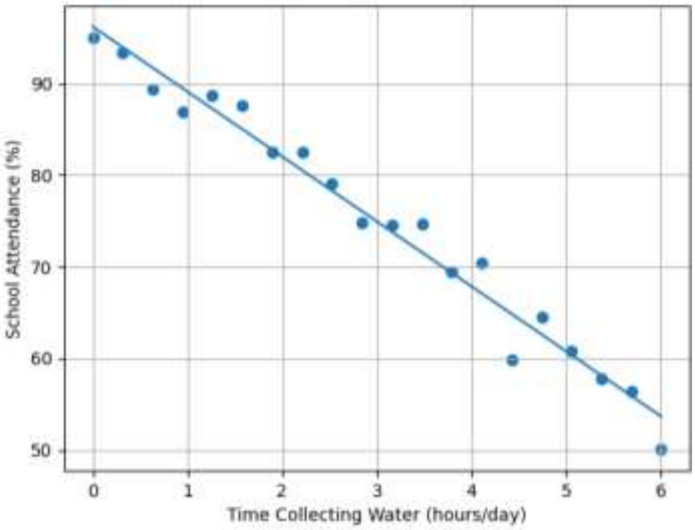
Fig. 2 demonstrates a clear positive relationship between water insecurity and child stunting. This suggests that limited water availability not only constrains hygiene but also affects food preparation and dietary diversity, amplifying malnutrition risks [5].

Similarly, Rakotomanana et al. (2020) reported that improved access to safe drinking water and sanitation services is positively associated with linear growth among children aged 6–23 months in East Africa [6].

These findings underscore the complex interaction between water access, food security, and child development, emphasizing that water scarcity contributes to both acute and chronic forms of malnutrition, including stunting.

Recent literature has increasingly focused on the psychological dimensions of water scarcity. Household water insecurity is associated with chronic stress, anxiety, and depression, driven by uncertainty, time burden, and social inequalities related to water access.

A large-scale meta-analysis by Kimutai et al. (2023), involving over 23,000 participants across 16 countries, confirmed a statistically significant association between water insecurity and common mental disorders, including depression and anxiety [7]. Supporting evidence from Aihara et al. (2016) shows that water insecurity is significantly linked to reduced quality of life and increased depressive symptoms among postnatal women in Nepal [8].



Water scarcity also affects socioeconomic conditions, particularly education (Fig. 3).

Fig. 4 shows a significant negative relationship between time spent collecting water and school attendance. This highlights the indirect but critical role of water access in human capital development [8].

Fig. 3 Impact of time spent collecting water on school attendance

These findings suggest that water scarcity should be considered not only a physical health risk but also a critical determinant of mental well-being.

Quality of life (QoL) is a multidimensional construct encompassing physical health, psychological well-being, social functioning, and environmental conditions. Water scarcity negatively affects all these dimensions simultaneously.

Recent studies emphasize that water insecurity leads to a cumulative burden of disease, stress, and socioeconomic disadvantage. Rhue et al. (2023) highlighted that water insecurity affects child health and well-being through multiple pathways, including disease exposure, nutritional deficits, and psychosocial stress [9].

The combined effect of these pathways results in reduced overall life satisfaction, increased vulnerability, and diminished resilience to environmental and economic shocks.

The existing body of literature provides robust evidence that water scarcity is a critical determinant of both physical and mental health, as well as overall quality of life. However, several research gaps remain.

First, there is a need for integrated models that simultaneously capture hydrological, health, and socioeconomic dimensions of water scarcity. Second, longitudinal studies are required to better understand causal relationships and long-term impacts. Third, region-specific analyses, particularly in semi-arid and mountainous regions such as the South Caucasus, remain limited.

Addressing these gaps is essential for developing effective water management and public health policies, especially in the context of climate change and increasing water demand.

Access to safe and sufficient drinking water is recognized as a fundamental human right and a core component of sustainable development. Despite global progress, many rural and mountainous regions continue to experience structural water deficits due to limited infrastructure, seasonal variability of water resources, and inefficient distribution systems.

Armenia presents a paradox of relatively abundant water resources at the national level, yet localized shortages persist due to spatial and temporal imbalances. In particular, the Artik community faces significant drinking water shortages despite the presence of surface water sources.

Previous studies emphasize that effective water resource management requires integrated approaches combining hydrological analysis, infrastructure planning, and socio-economic considerations. However, many local systems lack such integrated assessments.

This study aims to:

- quantify drinking water demand and deficit,
- analyze hydrological characteristics of the Geghadzor River basin,
- evaluate soil suitability for reservoir construction,
- provide a comprehensive engineering justification for a reservoir-based solution.

The relationship between water availability and crop yield has been extensively studied, demonstrating that yield response is strongly dependent on water deficit levels and irrigation efficiency, particularly under limited water conditions [15].

Effective water resource management requires long-term planning and integration of hydrological, engineering, and socio-economic factors to address future water challenges [29].

Conflict Setting

Global assessments indicate that water scarcity is intensifying due to increasing anthropogenic pressures and environmental degradation, posing significant risks to both human populations and freshwater ecosystems. Water security has emerged as a critical concept linking water availability, infrastructure, and socio-economic stability, highlighting the need for integrated management approaches in water-stressed regions. Access to safe and sufficient drinking water is recognized as a fundamental human right by the United Nations, emphasizing the responsibility of governments to ensure reliable water supply systems [17, 19, 20].

The Artik community illustrates a classic case of water availability versus accessibility conflict. While natural water resources exist, infrastructure limitations prevent reliable supply.
Population-based calculations indicate a total annual demand of approximately 1.45 million m^3, reflecting domestic water requirements [10]. However, existing supply systems cover only 50–55%, leading to widespread shortages.

Hydrological conditions further complicate the situation. The Geghadzor River basin is characterized by a small catchment area (~6.3 km^2), steep slopes ($I = 148‰$), and high peak discharge ($Q_1\% = 30.6$ m^3/s), resulting in rapid runoff and limited natural storage capacity [27].

The absence of storage infrastructure prevents effective regulation of seasonal flows, reinforcing the structural nature of water scarcity.

Research Results

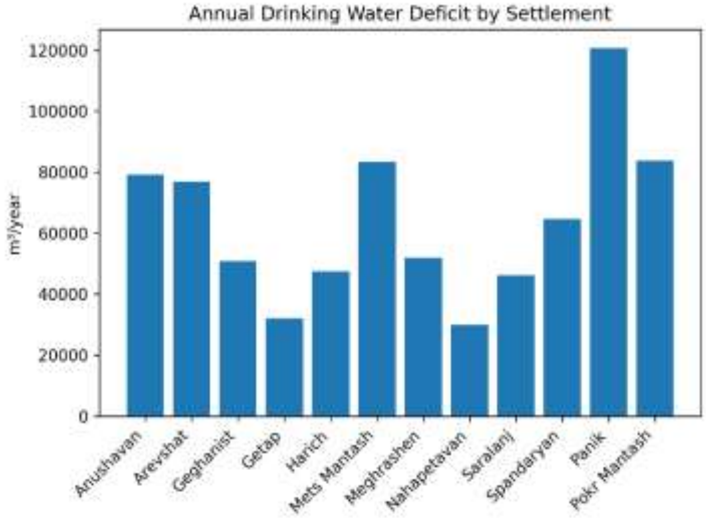
The quantitative analysis of drinking water demand and supply in the Artik community reveals a pronounced structural imbalance. Based on population-driven calculations using a standardized consumption rate, the total annual water demand reaches approximately 1.45 million m^3. However, the existing supply systems provide only 50–55% of this demand, resulting in a total annual deficit of 1,030,442.45 m^3.

This level of deficit corresponds to approximately 70% unmet demand, indicating severe water stress conditions. According to global water scarcity classifications, such levels of unmet demand place the study area within a high-risk category, where water shortages significantly affect living conditions and system reliability [21].

Importantly, the deficit is not episodic but persistent, reflecting a structural deficiency in the water supply system rather than temporary fluctuations.

Fig. 4 illustrates the distribution of annual drinking water deficit across the settlements of the Artik community. The results demonstrate that all settlements experience substantial water shortages, with deficit values directly correlated with population size and demand intensity.

The highest deficit levels are observed in larger settlements such as Panik and Mets Mantash, where both population density and water demand are significantly higher. However, smaller settlements also exhibit considerable relative deficits, indicating that the problem is not limited to high-demand areas but represents a system-wide issue.



This pattern confirms that the water deficit is structural rather than localized, arising from insufficient supply capacity and lack of storage infrastructure.

Fig. 4 Annual drinking water deficit (m^3/year) across settlements of the Artik community. The results reveal significant spatial variability in deficit magnitude, with consistently high values observed in all settlements, indicating a systemic imbalance between water demand and supply

The uniform presence of deficit across all settlements highlights the inability of the existing system to meet basic water demand requirements.

Furthermore, the magnitude of the deficit aligns with global definitions of severe water stress, reinforcing the urgency of implementing sustainable solutions such as reservoir-based regulation systems [21].

The distribution of water deficit across settlements demonstrates both absolute and relative variability. Larger settlements exhibit higher absolute deficits due to population concentration, while smaller settlements experience comparable relative shortages.

This indicates that the water deficit is not localized but systemic, affecting all settlements regardless of size. Such uniformity suggests that the underlying cause is not local infrastructure failure but rather a regional imbalance between water availability and supply capacity.

The spatial analysis further highlights that areas with higher demand are not matched by proportional increases in supply, reinforcing the need for centralized regulation mechanisms.

Fig. 5 presents the relationship between total water demand and actual supply across the settlements. The results clearly show that supply consistently falls short of demand, with a substantial portion of water requirements remaining unmet. This imbalance confirms that the system lacks sufficient capacity to deliver required volumes, emphasizing the need for storage and regulation infrastructure.

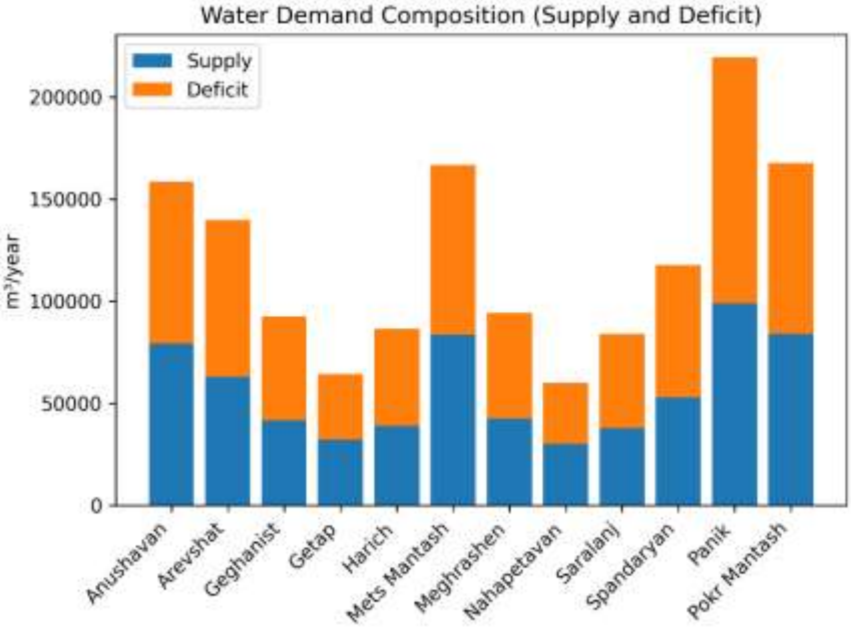


Fig. 5 Comparison of annual drinking water demand and available supply across settlements. The stacked representation highlights the proportion of unmet demand, illustrating the structural imbalance between required and delivered water volumes

Water supply coverage across the study area ranges between approximately 45% and 55%, reflecting low system efficiency. This limited coverage suggests that a significant portion of the population relies on irregular or alternative water sources, which may not meet quality standards.

From a system perspective, such coverage levels indicate:

- insufficient infrastructure capacity,
- lack of storage and regulation,
- inefficiencies in distribution networks.

The absence of buffering mechanisms, such as reservoirs, leads to direct dependence on instantaneous river flow, making the system highly vulnerable to seasonal variability [13].

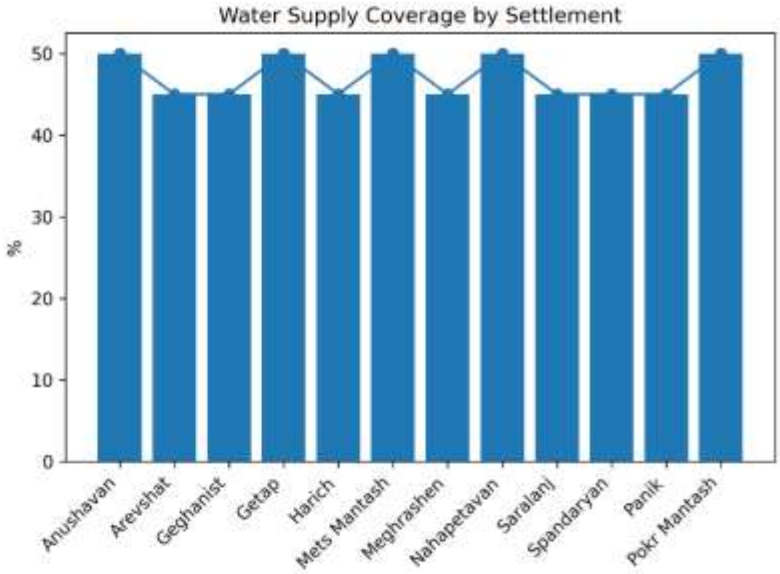


Fig.6 illustrates the percentage of water demand met by existing supply systems. Coverage levels range approximately between 45% and 55%, indicating that nearly half of the required water is not delivered.

Fig. 6 Water supply coverage (%) across settlements, indicating the proportion of demand satisfied by existing systems. The results show uniformly low coverage levels, reflecting limited system efficiency

This highlights systemic inefficiencies and the absence of buffering mechanisms such as reservoirs, leading to direct dependence on variable river flow.

The cumulative deficit analysis demonstrates how individual shortages aggregate into a large-scale system imbalance.

The cumulative curve shows a steady and continuous increase in unmet demand, indicating that the system operates under constant stress conditions.

This cumulative effect is particularly critical from a planning perspective, as it reflects the inability of the system to recover or compensate over time. Instead, deficits accumulate, increasing the overall vulnerability of the water supply system.

Such conditions are typical of systems lacking storage infrastructure, where short-term variability translates directly into long-term deficit accumulation.

Fig. 7 shows the cumulative deficit across all settlements, emphasizing the scale of total unmet demand. The steadily increasing curve reflects the persistent and aggregated nature of water shortages, indicating that the system operates under continuous stress. This cumulative effect reinforces the need for centralized water regulation solutions.

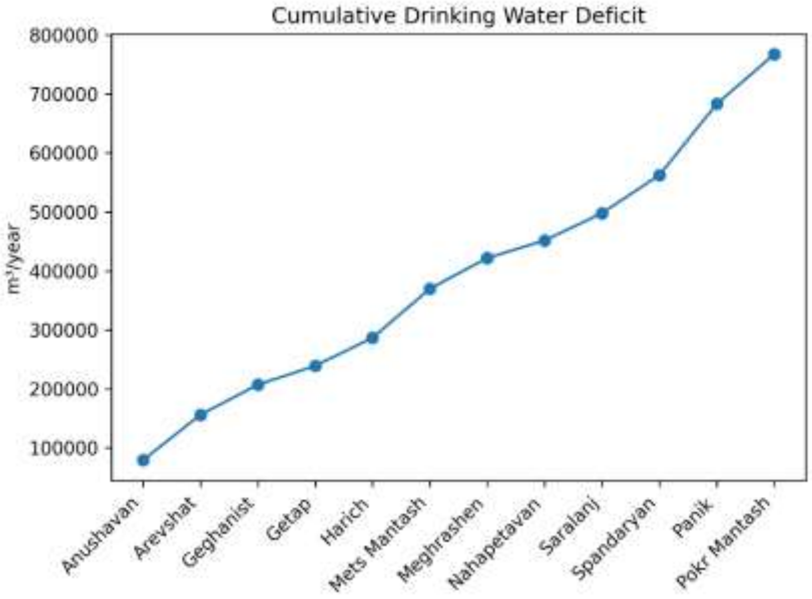


Fig. 7 Cumulative drinking water deficit across settlements, showing the aggregated magnitude of unmet demand and the progressive nature of system-wide water shortage

The hydrological characteristics of the Geghadzor River basin play a crucial role in shaping water availability. The basin is relatively small (~6.3 km^2) but exhibits steep slopes ($I = 148$‰), resulting in rapid runoff and limited natural retention.

Peak discharge values ($Q_{1\%} = 30.6$ m^3/s) indicate high flow intensity during peak events, while base flow conditions are significantly lower.

This contrast reflects a highly variable hydrological regime, typical of mountainous catchments.

Such variability creates a mismatch between water availability and demand:

- high flows occur during short periods,
- demand remains relatively constant throughout the year.

This temporal mismatch is a key driver of water deficit and underscores the need for flow regulation through storage systems [23, 27].

Fig. 8 presents the seasonal distribution of river discharge, highlighting a pronounced peak during spring months, primarily driven by snowmelt processes. The sharp increase in flow during April–May is followed by a rapid decline in summer and low-flow conditions during autumn and winter.

This strong seasonal variability creates a temporal mismatch between water availability and demand. While peak flows provide sufficient water volumes, they occur over a limited period, whereas water demand remains relatively constant throughout the year.

This imbalance underscores the necessity of storage infrastructure, such as reservoirs, to regulate flow and ensure stable supply.

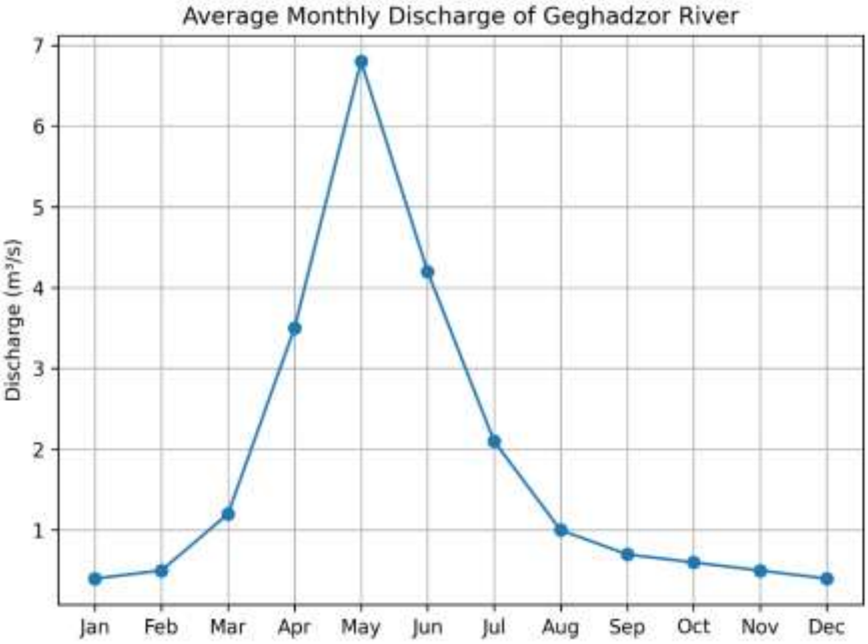


Fig. 8 Average monthly discharge of the Geghadzor River, illustrating strong seasonal variability with peak flow during spring snowmelt and low discharge during late summer and winter periods

Recent global assessments emphasize that water quality and availability are increasingly uncertain, with hidden risks that are not always reflected in existing monitoring systems [26].

Soil analysis indicates a predominantly clay-rich composition with low electrical conductivity and slightly alkaline conditions (pH ≈ 8.18). These properties suggest low permeability, which is favorable for reservoir construction.

From an engineering perspective, such soils provide:

- natural sealing capacity,
- reduced seepage losses,
- improved structural stability for embankment dams.

The presence of clay minerals (e.g., kaolinite) further enhances the suitability of the site for water retention structures. This significantly reduces the need for extensive artificial sealing measures, improving both technical feasibility and economic efficiency [24].

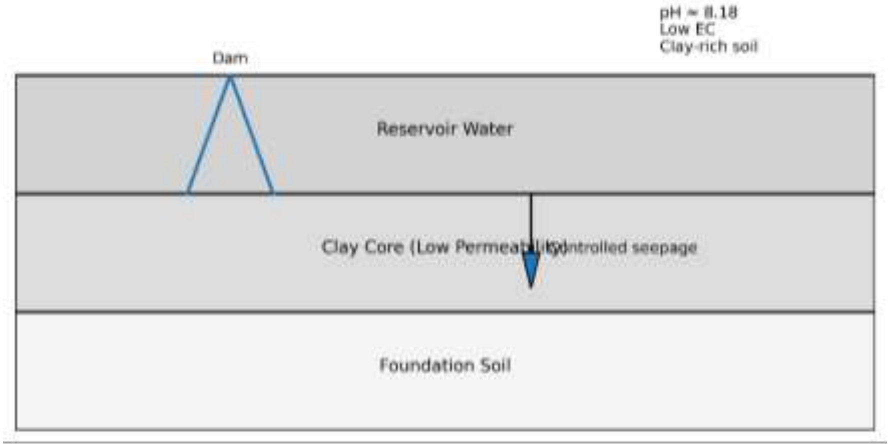


Fig. 9 Geotechnical cross-section of the proposed reservoir site showing clay-rich core and foundation conditions. The low-permeability clay layer обеспечивает natural sealing and reduces seepage losses, supporting the feasibility of reservoir construction

Fig. 9 illustrates the geotechnical cross-section of the proposed reservoir site. The presence of a clay-rich layer acting as a natural sealing core significantly reduces permeability and limits seepage losses.

The structural configuration of the foundation, combined with favorable soil properties such as low electrical conductivity and slightly alkaline pH (≈ 8.18), ensures stable hydro-mechanical conditions. These characteristics enhance reservoir performance and reduce the need for artificial lining measures.

The integration of geotechnical properties with hydrological conditions confirms the suitability of the site for reservoir construction from both engineering and environmental perspectives.

Fig. 10 Location of the Geghadzor reservoir

The proposed reservoir location is strategically positioned along the river axis, where topographic and geological conditions allow effective water storage. The alignment of the dam axis corresponds to a natural narrowing of the valley, optimizing construction feasibility and storage efficiency.

This spatial configuration confirms that the selected site is suitable for reservoir development, both from hydrological and engineering perspectives, and supports the broader objective of mitigating water deficit in the Artik community.

Conclusions

This study provides a comprehensive assessment of drinking water deficit in the Artik community through the integration of demand analysis, hydrological evaluation, geotechnical investigation, and GIS-based spatial interpretation.

The results demonstrate that the total annual drinking water deficit exceeds **1.03 million m³**, indicating a severe and persistent imbalance between water demand and available supply. The deficit is not localized but systemic, affecting all settlements within the study area and reflecting structural limitations of the existing water supply system.

Hydrological analysis of the Geghadzor River basin reveals a highly variable flow regime characterized by a small catchment area (~6.3 km²), steep slopes, and significant peak discharge. This variability leads to a temporal mismatch between water availability and demand, where excess water during short high-flow periods cannot be effectively utilized due to the absence of storage infrastructure.

Geotechnical analysis confirms that the presence of clay-rich, low-permeability soils provides favorable conditions for reservoir construction by minimizing seepage losses and enhancing water retention. These natural conditions significantly improve the feasibility and long-term reliability of the proposed solution.

The integration of hydrological, geotechnical, and socio-economic data within a GIS framework demonstrates that the selected reservoir location is optimal in terms of both engineering feasibility and spatial efficiency. The proximity of the reservoir site to deficit-affected settlements further enhances its practical value.

Overall, the findings confirm that reservoir construction represents a technically justified and strategically necessary solution for addressing drinking water scarcity in the Artik community. Beyond local significance, the study highlights the importance of integrated water resource management approaches in regions characterized by high hydrological variability and infrastructure constraints.

Policy Implications

The findings of this study have important implications for water resource management and policy development at both local and national levels.

First, the presence of a persistent and system-wide drinking water deficit highlights the need to prioritize water supply reliability as a key policy objective. Infrastructure investments should focus on developing storage systems, such as reservoirs, to regulate seasonal variability and ensure continuous supply.

Second, the results emphasize the importance of integrated water resource management (IWRM) approaches that combine hydrological, engineering, and socio-economic data. Policymaking should shift from fragmented solutions toward coordinated strategies that address both supply and demand components.

Third, given the strong spatial mismatch between water availability and demand, regional planning frameworks should incorporate GIS-based decision-making tools to optimize infrastructure placement and resource allocation.

Fourth, the study underscores the necessity of improving monitoring and data systems, including hydrological measurements and water quality assessments, to support evidence-based decision-making and reduce uncertainty in planning processes.

Finally, considering global trends in water scarcity, national policies should promote **long-term** resilience strategies**,** including climate adaptation measures, efficient water use, and diversification of water sources.

Future Research Directions

While this study provides a comprehensive assessment of drinking water deficit and reservoir feasibility, several areas require further investigation to enhance the robustness and applicability of the findings.

Future research should focus on the development of high-resolution hydrological models that incorporate climate change scenarios, enabling more accurate prediction of future water availability and system performance.

In addition, detailed sedimentation and reservoir lifetime analysis is required to assess long-term sustainability, particularly in small mountainous catchments characterized by high erosion rates.

Further investigation of water quality dynamics under reservoir conditions is also essential, including potential changes in turbidity, nutrient levels, and biological activity.

Another important direction is the integration of economic and financial modeling, including cost–benefit analysis and investment optimization, to support decision-making at the policy level.

Finally, expanding the GIS framework to include multi-criteria decision analysis would allow for more comprehensive evaluation of alternative reservoir locations and water management strategies.

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ՀԱՅԱՍՏԱՆԻ ՀԱՆՐԱՊԵՏՈՒԹՅԱՆ ԱՐԹԻԿ ՀԱՄԱՅՆՔԻ ԳՅՈՒՂԵՐՈՒՄ ԽՄԵԼՈՒ ՋՐԻ ԴԵՖԻՑԻՏԸ ՀԱՂԹԱՀԱՐԵԼՈՒ ՆՊԱՏԱԿՈՎ ՏԱՐԱԾԱՇՐՋԱՆԻ ՀԻԴՐՈԼՈԳԻԱԿԱՆ ՆԵՐՈՒԺԻ ՕՊՏԻՄԱԼԱՑՈՒՄ

Ա.Կ. Հարությունյան
Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Անվտանգ խմելու ջրի հուսալի հասանելիության ապահովումը շարունակում է մնալ կարևորագույն մարտահրավեր լեռնային շրջանների գյուղական բնակավայրերում, որտեղ ջրաբանական ցուցանիշների փոփոխականությունը և սահմանափակ ենթակառուցվածքները հանգեցնում են ջրի մշտական պակասի։ Մասնավորապես Արթիկ համայնքի բնակավայրերում, որտեղ խմելու ջրի տարեկան ընդհանուր պահանջարկը հասնում է 1.45 միլիոն մ^3, առկա ջրամատակարարումը ծածկում է պահանջարկի միայն 50-55%-ը, ինչը հանգեցնում է տարեկան 1.03 միլիոն մ^3 խմելու ջրի դեֆիցիտի: Հիդրոլոգիական վերլուծությունը հարակից համայնքում (Ծաղկահովիտ) բացահայտում է փոքր, բայց դինամիկ ավազան (F ≈ 6.3 կմ^2): Ուսումնասիրությունը ցույց է տալիս, որ 500 հազար քառակուսի մետր մակերեսով ջրամբարի կառուցմամբ հնարավոր է երկու համայնքներում ապահովել խմելու ջրի հուսալի մատակարարում և նպաստել ոռոգման զարգացմանը:

Բանալի բառեր՝ ջրի սակավություն; ջրամբարի նախագծում; ջրաբանական ցուցանիշների փոփոխականություն; խմելու ջրի մատակարարում

ОПТИМИЗАЦИЯ ГИДРОЛОГИЧЕСКОГО ПОТЕНЦИАЛА РЕГИОНА С ЦЕЛЬЮ ПРЕОДОЛЕНИЯ ДЕФИЦИТА ПИТЬЕВОЙ ВОДЫ В СЕЛАХ ОБЩИНЫ АРТИК РЕСПУБЛИКИ АРМЕНИЯ

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Обеспечение надежного доступа к безопасной питьевой воде остается важнейшей проблемой в сельских горных районах, где гидрологическая изменчивость и ограничения инфраструктуры приводят к постоянной нехватке воды. В данном исследовании представлена комплексная оценка дефицита питьевой воды в населенном пункте Артик (Армения), где общий годовой спрос на питьевую воду достигает 1,45 млн м^3, в то время как существующее водоснабжение покрывает лишь 50–55%, что приводит к дефициту, превышающему 1,03 млн м^3/год. Гидрологический анализ выявляет небольшой, но динамичный бассейн (F ≈ 6,3 км^2) в соседнем регионе (община Цахкаовит). Исследование

A.K. Harutyunyan

OPTIMIZATION OF THE HYDROLOGICAL POTENTIAL OF THE REGION IN ORDER TO OVERCOME THE SHORTAGE OF DRINKING WATER IN THE VILLAGES OF THE ARTIK COMMUNITY OF THE REPUBLIC OF ARMENIA

показывает, что строительство водохранилища площадью 500 тыс. квадратных метров представляет собой многофункциональное решение, обеспечивающее надежное питьевое водоснабжение и способствующее развитию орошения в обоих населенных пунктах.

Ключевые слова: дефицит воды; проектирование водохранилищ; гидрологическая изменчивость; питьевое водоснабжение.

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INTEGRATED ASSESSMENT OF ENVIRONMENTAL RISKS IN TAILINGS STORAGE FACILITIES BASED ON GEOCHEMICAL AND HYDROLOGICAL ANALYSIS

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Abstract

This study presents an integrated assessment of environmental risks associated with tailings storage facilities based on field and laboratory data. The analysis focuses on pH variability, heavy metal concentrations, and hydrological processes governing contaminant migration.

The results reveal significant spatial heterogeneity of geochemical conditions. Although water samples exhibit near-neutral pH values, extremely acidic conditions (pH down to 1.32) were identified in surface layers, indicating localized acid mine drainage processes. Heavy metals demonstrate strong accumulation in soils, confirming their long-term environmental persistence.

The study highlights the need for integrated risk management combining geochemical monitoring, engineering solutions, and management strategies.

Keywords: Tailings, Acid Mine Drainage, Heavy Metals, Hydrology, Environmental Risk, Geochemistry.

Introduction

Tailings storage facilities (TSFs) represent one of the most critical and long-lasting sources of environmental risk associated with mining activities. Unlike active industrial processes, tailings remain environmentally reactive for decades or even centuries, making them persistent sources of contamination in surrounding ecosystems.

Global incidents, including the Brumadinho dam disaster and the Mount Polley tailings dam failure, have highlighted the catastrophic consequences of insufficient monitoring and management of tailings systems[1][2]. These events demonstrated that failures in tailings storage are not only engineering problems but also systemic failures involving environmental, operational, and governance factors.

Environmental significance of tailings

The environmental impact of TSFs is primarily driven by two interrelated processes:

- acid mine drainage (AMD);
- heavy metal mobilization.

AMD is generated through the oxidation of sulfide minerals, leading to the formation of sulfuric acid and a significant decrease in pH values. This process enhances the solubility and mobility of metals, resulting in long-term contamination of water and soil systems (Tabl. 1). According to David K. Nordstrom (2011), AMD represents one of the most severe forms of mining-related pollution, capable of altering entire river systems and groundwater regimes[3].

Table 1

Process	Mechanism	Environmental impact
Acid Mine Drainage	Sulfide oxidation	pH decrease, metal mobilization
Heavy metal transport	Dissolution + migration	Water and soil contamination
Hydrological flow	Infiltration and runoff	Regional pollutant spread

Heavy metals as long-term pollutants

Heavy metals such as Cu, Zn, Pb, Cd, and As are among the most persistent contaminants associated with tailings. Unlike organic pollutants, these elements do not degrade and can accumulate in soils and sediments.

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[1] The Brumadinho dam disaster was a catastrophic tailings dam failure that occurred on January 25, 2019, near Brumadinho in Minas Gerais, Brazil. The collapse released a massive wave of mining waste from Vale S.A.’s Córrego do Feijão iron ore mine, killing 270 people and causing widespread environmental destruction.

[2] The Mount Polley tailings dam failure was a major industrial accident that occurred on August 4, 2014, at the Mount Polley copper-gold mine near Likely, British Columbia, Canada. A breach in the mine’s tailings storage facility released roughly 25 million m^3 of water and mine waste into nearby lakes and creeks, making it one of Canada’s worst mining environmental disasters.

[3] David K. Nordstrom is an American geochemist recognized for his pioneering research on acid mine drainage and aqueous geochemistry. His work has shaped scientific understanding of metal sulfide oxidation, contaminant transport, and geochemical modeling in natural and mining-impacted waters. Nordstrom’s research is widely cited across environmental science and hydrology.

Studies by Katherine A. Hudson-Edwards and David W. Blowes have shown that metal mobility is strongly controlled by geochemical conditions, particularly pH and redox potential[4][5].

Low pH environments significantly increase metal solubility, which enhances their transport through hydrological systems and increases ecological risk.

Hydrological control of contamination

Hydrological processes play a crucial role in the redistribution of contaminants from tailings storage facilities. These include:

- infiltration into groundwater systems;
- surface runoff during precipitation events;
- transport through river networks

Such processes can extend contamination far beyond the original tailings site, transforming local pollution into regional environmental problems.

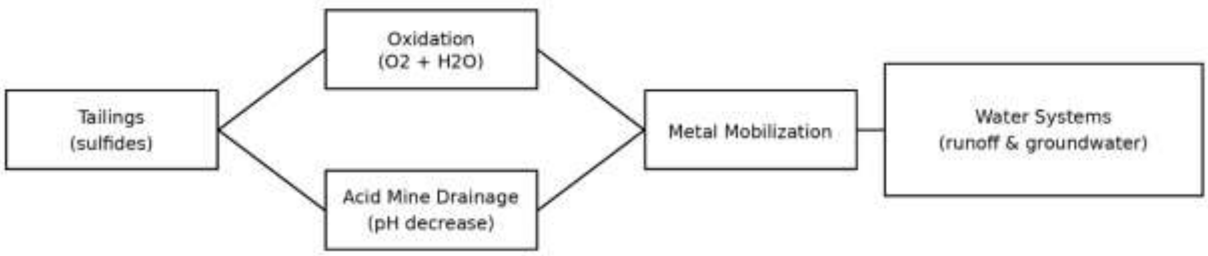

Fig. 1 Conceptual model of contaminant generation and transport in tailings storage facilities

Fig. 1 summarizes the main environmental-risk pathway in tailings storage facilities: sulfide oxidation generates acid mine drainage, which decreases pH and promotes heavy-metal mobilization. Mobilized contaminants are then transported through surface runoff and groundwater infiltration, creating exposure risks for soils, rivers, and biological receptors.

Hidden nature of environmental risk

One of the most critical challenges in assessing tailings-related risks is the discrepancy between apparent and actual environmental conditions.

Water samples may indicate near-neutral pH values, suggesting stability, while underlying soil layers can contain highly acidic zones responsible for ongoing metal mobilization.

This phenomenon has been described in multiple studies as a “hidden geochemical instability”, where contamination processes occur below the surface and remain undetected in conventional monitoring systems.

Research gap and novelty

Despite extensive research on tailings, several gaps remain:

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[4] Katherine A. Hudson-Edwards is a British environmental geochemist recognized for her expertise in the behavior and management of mine wastes. Her research focuses on metal contamination, remediation, and the environmental impacts of mining and mineral processing. She is a professor of sustainable mining and geochemistry at Birkbeck, University of London and a leading voice in sustainable resource extraction and pollution mitigation.

[5] David W. Blowes is a Canadian geochemist and environmental scientist known for his pioneering work on the geochemistry of mine wastes and groundwater remediation. A Professor at the University of Waterloo, he is recognized internationally for advancing understanding and prevention of acid mine drainage and contaminant transport in subsurface systems.

- недостаточная интеграция почвенных и водных данных;
- ограниченное внимание к локальным зонам закисления;
- недостаток комплексных моделей риска.

The present study addresses these gaps by integrating:

- pH variability;
- heavy metal concentrations;
- hydrological processes.

Tailings storage facilities (TSFs) have been widely recognized as complex environmental systems where geotechnical instability, geochemical reactivity, hydrological transport, and management failures interact over long periods. Unlike many industrial wastes, tailings remain reactive after mine closure, which makes post-closure monitoring and risk governance essential components of tailings safety.

Kossoff et al. emphasized that TSF risks are determined not only by dam construction and failure mechanisms, but also by the chemical nature of stored tailings, their long-term environmental impact, and the effectiveness of remediation measures. Their review highlights that tailings failures may generate severe downstream pollution, sediment contamination, and ecosystem degradation [1].

A major environmental mechanism associated with tailings is acid mine drainage (AMD). AMD is produced through the oxidation of sulfide minerals in the presence of oxygen and water, resulting in acidification and increased metal solubility. Blowes et al. describe AMD as a geochemical process capable of sustaining long-term contamination in mine-waste environments, especially where sulfide-rich materials remain exposed to atmospheric and hydrological conditions [2].

Heavy metal mobility is strongly controlled by pH, redox conditions, mineral composition, and hydrological pathways. Under acidic conditions, metals such as Cu, Zn, Fe, Mn, Pb, Cd, and As may become more soluble and mobile. This explains why apparently neutral water samples may not fully reflect the real environmental risk if acidic zones exist within tailings surface layers or internal deposits. This issue is especially important for the present study, where field and laboratory data show neutral-to-alkaline water pH in several cases, but highly acidic surface-layer conditions in some tailings facilities. Hydrological transport is another critical factor in tailings-related contamination. Infiltration, seepage, surface runoff, and river connectivity can transfer pollutants from tailings bodies into groundwater, soils, and downstream aquatic systems. This transforms localized contamination into a broader regional environmental risk. Therefore, tailings assessment should not be limited to chemical measurements alone, but should integrate hydrogeological context and pollutant migration pathways. From a safety-management perspective, historical analyses show that TSF failures often result from multiple interacting factors rather than a single technical cause. Azam and Li's review of tailings dam failures over the last century indicates that vulnerability is linked to dam construction practices, sequential raising, insufficient regulation, high post-closure maintenance costs, and extreme rainfall events [3].

Recent international governance frameworks also emphasize integrated management. The Global Industry Standard on Tailings Management, developed by UNEP, ICMM, and PRI, stresses that tailings facilities must be managed throughout their full lifecycle, including closure and post-closure, with the aim of preventing catastrophic failure and reducing risks to people and the environment [4].

Tailings management frameworks have evolved significantly over the past decades, incorporating both engineering design principles and long-term environmental considerations. The classical work of Steven G. Vick emphasizes that the stability of tailings dams must be evaluated not only during operation but also during closure and post-closure phases, where environmental risks often become more pronounced [5].

In parallel, geochemical studies highlight that sulfide-rich tailings remain reactive long after deposition. According to Dold, sulfide oxidation and secondary mineral formation control the release of acidity and metals, leading to long-term contamination potential in mine-waste environments [6]. These processes are strongly influenced by environmental conditions such as moisture, oxygen availability, and temperature.

Furthermore, comprehensive assessments of mine waste systems demonstrate that environmental impacts cannot be mitigated solely through containment strategies. As noted by Lottermoser, effective tailings management requires a combination of geochemical stabilization, hydrological control, and long-term monitoring [7]. This integrated approach is particularly relevant for regions where tailings interact with surface and groundwater systems.

Hudson-Edwards, Jamieson, and Lottermoser noted that mine wastes represent one of the largest waste streams worldwide and often contain high concentrations of elements that may severely affect ecosystems and human health [8]. Their work supports the need to treat tailings as long-term geochemical systems rather than inert storage materials.

Hydrological transport is another key factor in TSF risk formation. Infiltration, seepage, surface runoff, and river connectivity can transfer pollutants from tailings into soils, groundwater, and downstream aquatic systems. Rico et al. showed that tailings failure impacts are strongly connected with downstream run-out and pollutant transport, supporting the inclusion of hydrological pathways in risk assessment [9].

Modern studies also emphasize that tailings risks have socio-environmental dimensions. Cacciuttolo and colleagues concluded that mine tailings cannot be treated as inert or harmless materials, because they may generate toxic impacts on both communities and ecosystems [10]. This reinforces the need for integrated environmental-risk assessment and long-term governance.

Recent global-scale analyses of tailings failures indicate that the consequences of TSF incidents may extend far beyond the storage area and can affect river basins, settlements, agricultural lands, and regional water security. Islam et al. considered tailings failures at a global scale and emphasized the importance of impact assessment beyond the immediate failure site [11].

International governance frameworks now require lifecycle-based tailings management. The Global Industry Standard on Tailings Management, developed by UNEP, ICMM, and PRI, stresses that tailings facilities should be managed throughout design, operation, closure, and post-closure stages to prevent catastrophic failure and minimize risks to people and the environment. This aligns with the management component of the present article [12].

At a global scale, water systems are increasingly exposed to multiple anthropogenic pressures, including mining-related contamination. According to Vörösmarty et al., freshwater ecosystems are among the most threatened environmental systems, with water quality degradation driven by industrial pollution, land-use change, and hydrological alteration [13]. The authors emphasize that contaminants introduced into river systems can propagate over long distances, affecting not only local ecosystems but also regional water security and biodiversity. This perspective is particularly relevant for tailings storage facilities, where pollutants generated within confined areas may be transported through hydrological pathways, transforming localized contamination into basin-scale environmental risks.

Table 2

Key research directions in tailings risk assessment

Research direction	Key contribution	Relevance to this study
Tailings dam failure analysis	Identifies accident causes and downstream impacts	Supports the need for integrated risk assessment
Acid mine drainage	Explains sulfide oxidation and pH decrease	Interprets acidic surface-layer conditions
Heavy-metal mobility	Links low pH with metal solubility and migration	Supports Cu, Zn, Fe, Mn, Cr interpretation
Mine-waste geochemistry	Combines pH, sulfate, conductivity, and metals	Supports multi-parameter analysis
Hydrological transport	Explains runoff, seepage, and groundwater transfer	Supports contaminant migration analysis
Socio-environmental risk	Connects pollution with communities and ecosystems	Supports broader risk interpretation
Tailings governance	Emphasizes lifecycle management and monitoring	Supports management innovation component

Conflict Setting

The reviewed literature shows that TSF risks are usually studied through separate disciplinary lenses: geotechnical failure, AMD chemistry, metal mobility, hydrological transport, or governance. However, several gaps remain. First, many monitoring approaches focus mainly on water chemistry, although soil and surface-layer geochemistry may reveal hidden acidification zones. Second, environmental data are often separated from management decision-making, which limits their practical use for risk reduction. Third, few studies combine pH, metals, hydrology, and management-oriented interpretation within one integrated framework.

The present study addresses these gaps by integrating real field and laboratory data on water and surface-layer chemistry with a broader interpretation of environmental risk and tailings safety management.

The aim of this study is to provide an integrated assessment of environmental risks in tailings storage facilities based on real field and laboratory data, focusing on the interaction between geochemical and hydrological factors.

Research Results

Study area and tailings facilities

The study was conducted across multiple tailings storage facilities (TSFs) located in mining regions characterized by long-term ore processing and waste accumulation. The selected sites represent different geochemical and hydrological conditions, allowing for comparative analysis of environmental risks. The investigated tailings facilities include: Voghji, Pukhrut, Darazor, Dastakert, Artsvanik, Terterasar, Hankasar, Sotk. These sites were selected based on their environmental relevance, variability of geochemical conditions, and availability of field data.

Sampling strategy

Field sampling was conducted to capture both spatial variability and environmental heterogeneity of tailings systems.

Two main sample types were collected:

- water samples (surface water and pore water);
- soil samples (surface layers of tailings deposits).

Sampling locations were selected to represent:

- different zones within tailings facilities;
- areas with potential acidification;
- zones influenced by water flow and runoff.

To ensure representativeness, samples were collected from multiple points within each site.

Table 3

Study sites and sampling matrix

Site	Sample type	Parameters analyzed
Voghji	Water / Soil	pH, Cu, Zn, Fe, Mn
Pukhrut	Water / Soil	pH, Cu, Zn, Fe, Mn
Darazor	Water / Soil	pH, Cu, Zn, Fe, Mn
Dastakert	Water / Soil	pH, Cu, Zn, Fe, Mn
Artsvanik	Soil	pH, metals
Terterasar	Water / Soil	pH, metals
Hankasar	Water / Soil	pH, metals
Sotk	Soil	pH, metals

Laboratory analysis

Laboratory analyses were performed using a Photolab 7100 VIS spectrophotometer, ensuring high precision in chemical measurements.

The following parameters were determined: pH; Electrical conductivity; Total dissolved solids; Heavy metals (Cu, Zn, Fe, Mn, Cr and others).

Analytical methods:

- Spectrophotometric analysis;
- Standard water and soil testing procedures;
- Calibration using certified reference solutions.

Data processing and interpretation

The collected data were analyzed using a combination of:

- comparative analysis between sites;
- range-based interpretation (minimum–maximum values);
- identification of spatial variability.

Particular attention was given to:

- correlation between pH and metal concentrations;

- differences between water and soil environments;
- identification of anomalous values.

Conceptual modeling approach

To interpret the environmental processes, a conceptual framework was applied linking:

- sulfide oxidation;
- acid generation;
- metal mobilization;
- hydrological transport

This approach allows the integration of geochemical and hydrological data into a unified environmental risk model.

Reliability and limitations

The reliability of the results is supported by:

- use of calibrated laboratory equipment;
- standardized analytical procedures;
- consistency of measurements across sites.

However, several limitations should be noted:

- spatial heterogeneity of tailings systems;
- temporal variability (seasonal effects not fully captured);
- limited number of sampling points in some locations.

pH variability and acidification processes

The analysis of pH values revealed pronounced spatial variability across the investigated tailings storage facilities. While water samples generally exhibited near-neutral conditions (pH ≈ 6.6–7.5), surface and soil layers showed significantly lower values in certain locations. The most critical conditions were identified in Dastakert and Terterasar, where soil pH reached extremely acidic values (down to 1.32), indicating active acid mine drainage (AMD) processes. Localized acidification zones act as primary drivers of geochemical instability, even when bulk water conditions appear stable.

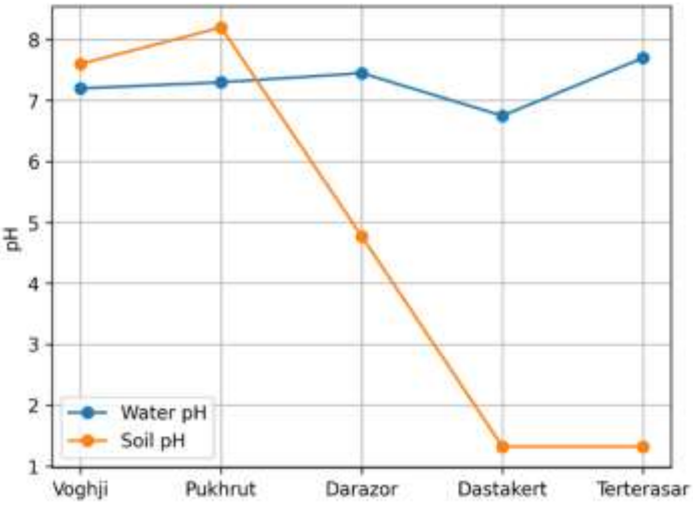

Fig. 2 Comparison of pH values in water and soil samples across tailings storage facilities

Fig. 2 compares pH values between water and soil environments across the studied tailings storage facilities. While water samples generally exhibit near-neutral conditions, soil layers show significantly lower pH values in several sites. This discrepancy indicates the presence of localized acidification zones that are not reflected in bulk water measurements.

Table 4
pH distribution in ailings systems

Site	Water pH	Soil pH	Interpretation
Voghji	6.9–7.4	7.5–7.8	Stable
Pukhrut	7.2–7.4	7.8–8.7	Stable
Darazor	7.4–7.5	4.77	Local acidification
Dastakert	6.7–6.8	1.32	Extreme AMD
Terterasar	7.4–8.0	1.32	Strong heterogeneity

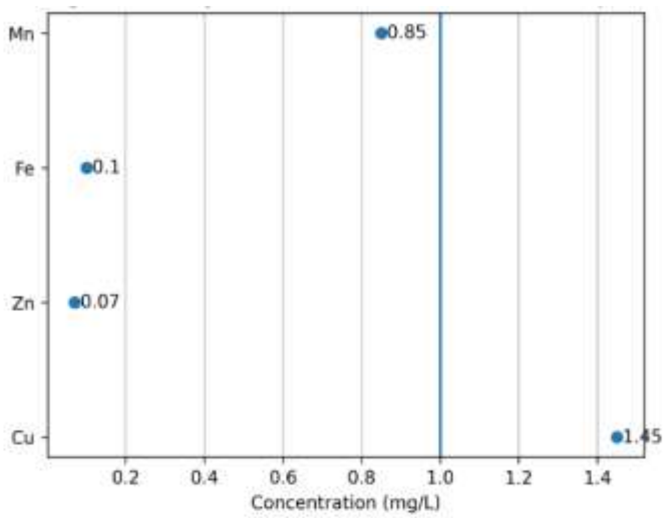

Fig. 3 Heavy metal concentrations in water samples across selected tailings storage facilities. The vertical line indicates a reference threshold level

Fig. 3 presents the distribution of heavy metal concentrations in water samples. The results show that certain elements, particularly Cu, approach or exceed reference levels, indicating active geochemical processes and potential environmental risk. The variability among metals reflects differences in mobility and geochemical behavior under site-specific conditions.

Discussion

Comparison with international studies

The results obtained in this study are consistent with international findings on tailings storage facilities, particularly regarding the dominant role of geochemical processes in environmental risk formation.

Previous studies (e.g., Kossoff et al., 2014; Dold, 2010 [1, 6]) have shown that tailings systems often exhibit significant spatial variability, where localized geochemical conditions may differ substantially from bulk measurements. The present study confirms this observation: although water samples generally display near-neutral pH values, soil layers contain highly acidic zones (pH down to 1.32), indicating active acid mine drainage processes.

This discrepancy aligns with the findings of Nordstrom (2011), who emphasized that mine waters may appear chemically stable while still carrying dissolved contaminants originating from acidic microenvironments [14].

Acid mine drainage as a controlling factor

The identification of localized acidic zones highlights the critical role of acid mine drainage (AMD) as a primary driver of contamination.

International studies have demonstrated that AMD significantly increases the solubility and mobility of metals. Blowes et al. showed that sulfide oxidation processes lead to long-term acid generation, which may persist even after mine closure [2].

The results of this study confirm that AMD is not uniformly distributed, but rather occurs in localized zones, which act as “hotspots” of contamination. This finding is important because it explains why conventional monitoring based on water sampling may underestimate environmental risk.

Heavy metal behavior and accumulation

The observed distribution of heavy metals is consistent with global research indicating that metals tend to accumulate in solid phases rather than remain in aqueous solutions.

Lottermoser (2010) demonstrated that mine wastes often act as long-term reservoirs of contamination due to metal retention in soils and sediments. Similarly, Hudson-Edwards et al. (2011) emphasized that mine tailings contain significant quantities of potentially toxic elements that can be released under changing environmental conditions [7, 8].

The results of the present study clearly show that soil concentrations are significantly higher than those in water, confirming the accumulation effect and long-term environmental persistence of metals.

Role of hydrological processes

Hydrological transport plays a crucial role in the redistribution of contaminants.
International case studies (Rico et al., 2008; Islam et al., 2021) have demonstrated that contaminants originating from tailings can be transported through river systems and groundwater, affecting large areas beyond the original source [9].

The findings of this study support this mechanism, as the presence of mobile metals in water samples indicates ongoing transport processes. This confirms that tailings-related pollution should be considered not only as a local problem but also as a regional environmental risk.

Management implications

A key implication of this study is that environmental risk in tailings storage facilities cannot be effectively mitigated through engineering solutions alone.

The Global Industry Standard on Tailings Management emphasizes the importance of lifecycle-based management, including monitoring, risk assessment, and governance.

The results of this study support this approach and demonstrate that:

- monitoring must include both water and soil;
- localized acidic zones must be identified;
- geochemical data must be integrated into management decisions.

The results demonstrate that environmental stability in tailings systems is often only apparent. While bulk water chemistry may suggest neutral conditions, underlying geochemical processes can sustain active contamination pathways.This hidden instability represents a critical challenge for environmental monitoring and risk assessment, as it may lead to significant underestimation of long-term environmental impacts.

Conclusions

Main findings

1. Tailings storage facilities exhibit high spatial variability in geochemical conditions.

2. Localized acid mine drainage zones (pH as low as 1.32) are the primary drivers of metal mobilization.
3. Heavy metals show strong accumulation in soils, confirming their long-term environmental persistence.
4. Hydrological processes enable the transport of contaminants beyond the tailings site, creating regional environmental risks.

Scientific contribution

5. This study demonstrates that environmental risk assessment must integrate water and soil data to capture hidden geochemical processes.
6. The results provide evidence that conventional monitoring approaches may underestimate environmental risk if localized acidification zones are not considered.

Practical implications

7. Effective tailings management requires:
    - integrated monitoring (water + soil);
    - identification of geochemical hotspots;
    - incorporation of geochemical data into management systems.

Future research

8. Further research should focus on:
    - quantitative risk modeling;
    - long-term monitoring systems;
    - integration of geochemical and hydrological models.

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ՊՈՉԱՄԲԱՐՆԵՐՈՒՄ ԷԿՈԼՈԳԻԱԿԱՆ ՌԻՍԿԵՐԻ ԳՆԱՀԱՏՈՒՄ՝ ՀԻՄՆՎԱԾ ԵՐԿՐԱՔԻՄԻԱԿԱՆ և ՀԻԴՐՈԼՈԳԻԱԿԱՆ ՎԵՐԼՈՒԾՈՒԹՅԱՆ ՎՐԱ

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[3]Ճարտարապետության և շինարարության Հայաստանի ազգային համալսարան

Ներկայացնում է պոչամբարների շահագործման հետ կապված բնապահպանական ռիսկերի համապարփակ գնահատական՝ հիմնված դաշտային և լաբորատոր տվյալների վրա:

Հետազոտության արդյունքները բացահայտում են երկրաքիմիական պայմանների զգալի տարածական բազմազանությունը: Չնայած ջրի նմուշները ցույց են տալիս չեզոքին մոտ pH արժեքներ, սակայն մակերեսային շերտերում հայտնաբերվել են չափազանց թթվային պայմաններ (մինչև 1.32): Ծանր մետաղները զգալի կուտակում են ցուցաբերում հողերում, ինչը հաստատում է դրանց երկարատև պահպանումը շրջակա միջավայրում: Ուսումնասիրությունը ընդգծում է ինտեգրված ռիսկերի կառավարման անհրաժեշտությունը՝ համատեղելով երկրաքիմիական մոնիթորինգը, ինժեներական լուծումները և կառավարման ռազմավարությունը:

Հետազոտության արդյունքները ցույց են տալիս, որ պոչամբարներում շրջակա միջավայրի կայունությունը հաճախ միայն թվացյալ է: Չնայած ջրի քիմիան ընդհանուր առմամբ կարող է ցույց տալ չեզոք պայմաններ, հիմքում ընկած երկրաքիմիական գործընթացները կարող են նպաստել ակտիվ աղտոտման ուղիներին: Այս թաքնված անկայունությունը լուրջ մարտահրավեր է ներկայացնում շրջակա միջավայրի մոնիթորինգի և ռիսկերի գնահատման համար, քանի որ այն կարող է հանգեցնել երկարաժամկետ շրջակա միջավայրի վրա ազդեցության զգալի թերագնահատման:

Բանալի բառեր՝ պոչեր, հանքի թթվային հոսքեր, ծանր մետաղներ, հիդրոլոգիա, շրջակա միջավայրի ռիսկ, երկրաքիմիա:

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INTEGRATED ASSESSMENT OF ENVIRONMENTAL RISKS IN TAILINGS STORAGE FACILITIES BASED ON GEOCHEMICAL AND HYDROLOGICAL ANALYSIS

КОМПЛЕКСНАЯ ОЦЕНКА ЭКОЛОГИЧЕСКИХ РИСКОВ В ХВОСТОХРАНИЛИЩАХ НА ОСНОВЕ ГЕОХИМИЧЕСКОГО И ГИДРОЛОГИЧЕСКОГО АНАЛИЗА

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Представлена комплексная оценка экологических рисков, связанных с хранилищами отходов обогащения, на основе полевых и лабораторных данных. Анализ сосредоточен на изменчивости pH, концентрациях тяжелых металлов и гидрологических процессах, определяющих миграцию загрязняющих веществ.

Результаты показывают значительную пространственную неоднородность геохимических условий. Хотя пробы воды демонстрируют значения pH, близкие к нейтральным, в поверхностных слоях были выявлены крайне кислые условия (pH до 1,32), что указывает на локализованные процессы кислотного дренажа шахт. Тяжелые металлы демонстрируют сильное накопление в почвах, подтверждая их долговременную стойкость в окружающей среде. Исследование подчеркивает необходимость комплексного управления рисками, сочетающего геохимический мониторинг, инженерные решения и стратегии управления.

Экологическая стабильность в хвостохранилищах часто носит лишь кажущийся характер. Хотя химический состав воды в целом может указывать на нейтральные условия, лежащие в основе геохимические процессы могут поддерживать активные пути загрязнения. Эта скрытая нестабильность представляет собой серьезную проблему для экологического мониторинга и оценки рисков, поскольку она может привести к значительной недооценке долгосрочных экологических последствий.

Ключевые слова: хвосты, кислые шахтные стоки, тяжелые металлы, гидрология, экологический риск, геохимия.

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RESOURCE AUDIT–BASED OPTIMIZATION OF INDUSTRIAL ENTERPRISE PERFORMANCE THROUGH MANAGEMENT AND TECHNOLOGICAL INNOVATIONS

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Abstract

This study addresses the problem of improving the efficiency of industrial and construction enterprises under conditions of resource imbalance, regulatory limitations, and increasing technological complexity. Despite the extensive body of research on resource management, existing approaches often remain fragmented, focusing separately on human, material–technical, and informational resources, while insufficient attention is given to their integrated management and the role of regulatory enforcement.

The paper proposes a decision-based conceptual model for enterprise optimization, in which resource audit is positioned as a central diagnostic and management tool. The model enables the identification of systemic imbalances, including competency gaps, technological mismatches, inefficient resource allocation, and deficiencies in regulatory compliance and enforcement. Based on this diagnosis, a structured set of corrective actions is introduced, including personnel tuning, technological modernization, digital monitoring systems, and governance improvements.

A key novelty of the research is the integration of institutional and regulatory dimensions into the resource management framework, emphasizing that enterprise efficiency depends not only on resource availability but also on the quality of legal frameworks and their effective implementation. The model incorporates a feedback-driven mechanism, ensuring continuous adaptation and long-term sustainability.

The results demonstrate that the proposed approach provides a comprehensive methodological basis for improving efficiency, reducing risks, enhancing compliance, and supporting sustainable development in industrial and construction enterprises.

Keywords: resource audit, industrial enterprise, construction sector, resource imbalance, regulatory framework, enforcement, digital transformation, optimization model.

Introduction

In recent decades, the improvement of industrial enterprise performance has increasingly been examined within the context of integrated resource management, digital transformation, and the implementation of advanced technological innovations.

Contemporary research demonstrates that traditional management approaches, which rely on the isolated evaluation of individual resource components (human, material, and financial), are no longer sufficient to ensure sustainable efficiency under conditions of rapid market dynamics and accelerating technological change.

The concept of an enterprise’s resource potential encompasses the totality of all resource types that ensure its functioning, including human, material and technical, information, and financial resources.

Studies in enterprise management indicate that the key factor in improving efficiency lies not merely in the availability of resources, but in their coordinated and balanced utilization.

Strategic management research further emphasizes that imbalances among different resource categories lead to decreased productivity and increased operational costs.

A specific case of industrial activity is the mining and metallurgical sector, which is characterized by high capital intensity, complex technological processes, and significant environmental and operational risks [1, 2]. Unlike many other industries, mining and metallurgical production involves continuous interaction with natural systems, variable raw material quality, and geographically dispersed assets, which increases the complexity of resource management [3].

Furthermore, the sector is highly dependent on the coordinated functioning of infrastructure, equipment, and skilled personnel, making the balance between human and material–technical resources critically important [4]. These characteristics, combined with increasing environmental and regulatory pressures, require the implementation of integrated management approaches, including resource audit and innovation-driven optimization [5]. The study [6] demonstrates that industrial activities, including mining, represent one of the major drivers of impacts on water resources and biodiversity at the global scale. The authors show that localized contamination can propagate through hydrological systems, evolving into regional and even global environmental risks. The study [7] analyzes the socio-economic impacts of mining activities and demonstrates that such projects are associated with complex governance challenges, resource redistribution, and population displacement. The authors emphasize that effective management requires not only technical solutions but also comprehensive systemic and institutional approaches.

Resource audit has emerged as one of the most advanced and effective instruments for comprehensive enterprise assessment. In contrast to conventional audit approaches—primarily financial or technological in scope—resource audit provides a systemic evaluation of all interconnected components of an enterprise and enables the identification of structural imbalances across them. Extant research indicates that the systematic implementation of resource audit facilitates the detection of critical inefficiencies and management bottlenecks, reveals imbalances between resource availability and utilization, and supports the formulation of robust, data-driven strategic development pathways. In particular, Neely A. et al. [8] emphasize the importance of integrated performance measurement systems that align resources with strategic objectives, while Wamba SF et. al [9] highlight the role of data analytics in transforming organizational decision-making processes. Its significance is further amplified in the context of digital transformation, where the exponential growth of data availability necessitates integrated analytical frameworks capable of converting heterogeneous data streams into actionable managerial insights.

Human capital represents one of the key determinants of industrial enterprise performance. Contemporary research indicates that insufficient workforce qualification levels or a mismatch between employee competencies and production requirements leads to decreased labor productivity, inefficient utilization of equipment, and increased technological risks. In particular, [10] highlights the role of human capital as a fundamental driver of productivity, while [11] demonstrate that alignment between human resources and organizational strategy significantly influences firm performance. In this context, the concept of adaptive competency development has gained increasing attention, emphasizing flexible systems of education, training, and continuous professional upskilling aligned with evolving industrial demands.

The material and technical base of an enterprise comprises production equipment, technologies, and infrastructure. Recent studies indicate that investments in equipment modernization, without corresponding improvements in workforce capabilities, do not result in significant efficiency gains. In particular, [12] demonstrate that technological advancement must be complemented by human skill development, while [13] highlight the importance of integrating human and technological systems within Industry 4.0 environments. Thus, achieving sustainable performance improvements requires the synchronized development of both human capital and material–technical resources.

In contemporary conditions, digital technologies play a central role in enterprise management, encompassing monitoring systems, analytical platforms, and integrated information management systems. These technologies enhance process transparency, improve the quality of managerial decision-making, and contribute to cost reduction through increased operational efficiency. In particular, [14] demonstrate that digital and analytics-driven systems enable real-time monitoring and adaptive decision-making, while [15] highlight the transformative impact of Industry 4.0 technologies on organizational performance and competitiveness. The implementation of managerial and technological innovations is therefore widely recognized as a key driver of enterprise competitiveness in the context of digital transformation.

The construction sector represents a distinct domain within industrial activity, characterized by project-based operations, high uncertainty, multi-stakeholder coordination, and a strong dependence on regulatory frameworks. Unlike continuous production industries, construction projects are inherently non-repetitive, geographically dispersed, and highly sensitive to contractual conditions, permitting procedures, and compliance requirements.

In the context of the Republic of Armenia, one of the most critical constraints affecting the efficiency of construction activities is the incompleteness and fragmentation of the legislative and regulatory framework governing the sector [16]. This limitation is particularly evident in the domain of design and cost estimation, where the absence of comprehensive and consistently enforced regulations creates significant challenges for project planning and execution. Empirical evidence indicates that compressed project timelines, insufficient funding, and weak enforcement of regulatory requirements often result in incomplete or technically inadequate design–estimate documentation, increasing the likelihood of errors, cost overruns, and safety risks [16]. Furthermore, the lack of clear accountability between clients and design organizations leads to systemic imbalances that reduce transparency and overall project efficiency.

These challenges are consistent with international findings, which indicate that regulatory uncertainty and weak institutional environments significantly increase transaction costs and reduce investment efficiency [17]. In large-scale construction and infrastructure projects, inadequate planning and insufficient governance mechanisms are among the primary causes of systematic cost overruns and project delays [18]. From a theoretical perspective, the effectiveness of construction systems is strongly conditioned by the quality of institutional frameworks. Technological improvements alone are insufficient without supportive regulatory structures and governance mechanisms [19]. Moreover, efficient resource allocation requires a well-defined legal environment and minimized transaction costs, as established in the theory of economic organization [20].

Therefore, the construction sector requires not only regulatory improvements but also the implementation of integrated management approaches. In this context, resource audit emerges as a critical tool for identifying mismatches between planned and actual resource utilization, improving cost control, and enhancing accountability across all stages of project implementation.

Conflict Setting

Despite the substantial body of research in this field, several critical challenges remain unresolved, including the lack of an integrated approach to resource management, the fragmented consideration of human and material–technical potential, the insufficient application of resource audit in managerial practice, the limited integration of digital technologies into resource analysis processes, as well as deficiencies in the development and enforcement of regulatory and legal frameworks governing industrial and construction activities [21, 22].

These gaps highlight the need for a unified methodological framework capable of integrating diverse resource components into a coherent management system, while also ensuring the effective implementation and enforcement of existing legal and regulatory provisions.

In response to these limitations, the present study proposes an integrated approach to industrial enterprise optimization based on resource audit principles, combining human capital development, modernization of material–technical infrastructure, the application of digital and innovation-driven management tools, and the improvement of regulatory mechanisms with a focus on compliance and accountability.

The proposed framework contributes to the existing body of knowledge by bridging the gap between theoretical resource management concepts and their practical implementation, offering a systematic mechanism for improving efficiency, enhancing decision-making, strengthening regulatory compliance, and ensuring the sustainable development of industrial enterprises.

Research Results

Modern industrial enterprises operate under conditions of high uncertainty, rapid technological change, and increasing requirements for resource efficiency. In this context, there is a growing need to transition from fragmented management of individual resource types toward an integrated system of resource potential management. The proposed conceptual model is based on the premise that enterprise performance is determined not by the absolute level of resources, but by the degree of their coordination and balance.

Within the framework of the model, the resource potential of an enterprise is considered as a system comprising the following interrelated components: human capital; material and technical resources; information resources; managerial capacity Each of these components evolves dynamically; however, their isolated development leads to a reduction in overall system efficiency.

A central issue addressed in the model is the imbalance between components of the resource potential. In practice, this manifests as:

- advanced equipment combined with insufficiently qualified personnel;
- highly skilled workforce operating with outdated technological infrastructure;
- availability of data without adequate analytical capabilities;
- existence of regulatory frameworks without effective enforcement mechanisms.

The latter is particularly relevant for the construction sector, where discrepancies between adopted legal provisions and their practical implementation lead to reduced project efficiency and increased operational risks.

Within the proposed model, resource audit is positioned as a key diagnostic and managerial tool. It performs the following functions:

- identification of imbalances between system components;
- evaluation of resource utilization efficiency;
- detection of critical constraints;
- formulation of optimization pathways.

Resource audit enables the transition from intuitive management to evidence-based and structured decision-making.

Fig. Decision-based conceptual model for industrial enterprise optimization integrating resource audit, system imbalance diagnosis, regulatory and enforcement factors, and feedback-driven corrective actions

The model introduces the concept of adaptive competency development (“personnel tuning”), which includes:

- targeted development of critical competencies;
- flexible systems of training and reskilling;
- alignment of workforce capabilities with technological advancement.

This approach allows reducing the gap between production requirements and actual workforce capacity.

Digital technologies act as an integrating element within the model, enabling:

- data acquisition and processing
- real-time monitoring of resource conditions
- support for managerial decision-making.

The integration of digital tools enhances the effectiveness of resource audit and increases system adaptability.

Unlike many existing models, the proposed framework explicitly incorporates the institutional environment.

The effectiveness of resource management depends on:

- the quality of regulatory and legal frameworks;
- the mechanisms of their enforcement;
- the level of compliance across stakeholders

Thus, optimization cannot be achieved without the simultaneous improvement of both managerial and regulatory systems.

The proposed model represents an integrated system in which, resources:

- are assessed through resource audit;
- imbalances are identified;
- managerial and technological interventions are applied;
- an optimal system state is achieved.

Conclusions

This study demonstrates that improving the efficiency of industrial enterprises requires a transition from fragmented resource management toward an integrated, system-based approach. The findings confirm that enterprise performance is determined not by the absolute availability of resources, but by the degree of their coordination, balance, and alignment with operational and regulatory requirements.

A key contribution of the research is the development of a decision-based conceptual model in which resource audit functions as a central mechanism for diagnosing system imbalances, including human, material–technical, informational, and managerial inconsistencies. The model extends existing approaches by explicitly incorporating regulatory and institutional factors, particularly the role of legal frameworks and the effectiveness of their enforcement, which are often overlooked in traditional resource management studies.

The analysis highlights that one of the most critical constraints in the construction and industrial sectors, particularly in the context of developing economies, is not only the incompleteness of the regulatory framework but also the insufficient implementation and enforcement of existing legal provisions. This results in systemic inefficiencies, increased operational risks, and reduced investment effectiveness.

The proposed model introduces a structured decision-making process that links resource audit, imbalance identification, and corrective actions, including personnel tuning, technological modernization, digital monitoring, and governance improvements. The inclusion of a feedback loop ensures continuous system adaptation and supports sustainable enterprise development.

Overall, the research contributes to bridging the gap between theoretical resource management concepts and their practical application. It provides a methodological foundation for enhancing efficiency, strengthening regulatory compliance, and improving decision-making processes in industrial and construction enterprises.

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ԱՐԴՅՈՒՆԱԲԵՐԱԿԱՆ ՁԵՌՆԱՐԿՈՒԹՅՈՒՆՆԵՐԻ ԱՐԴՅՈՒՆԱՎԵՏՈՒԹՅԱՆ ՕՊՏԻՄԱԼԱՑՈՒՄ՝ ՌԵՍՈՒՐՍԱՅԻՆ ԱՈՒԴԻՏԻ ՀԻՄԱՆ ՎՐԱ՝ ԿԱՌԱՎԱՐՄԱՆ և ՏԵԽՆՈԼՈԳԻԱԿԱՆ ՆՈՐԱՐԱՐՈՒԹՅՈՒՆՆԵՐԻ ԿԻՐԱՌՄԱՄԲ

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Աշխատանքը նվիրված է արդյունաբերական և շինարարական ձեռնարկությունների արդյունավետության բարձրացման խնդրին՝ ռեսուրսների դիսբալանսի, օրենսդրական սահմանափակումների և տեխնոլոգիական բարդության աճի պայմաններում: Չնայած ռեսուրսների կառավարման ոլորտում առկա լայնածավալ հետազոտություններին, գործող մոտեցումները հիմնականում ունեն տարանջատված բնույթ՝ առանձին դիտարկելով կադրային, նյութատեխնիկական և տեղեկատվական ռեսուրսները՝ անտեսելով դրանց ինտեգրված կառավարումը և իրավական պահանջների կատարման կարևորությունը: Առաջարկվում է ձեռնարկության օպտիմալացման որոշումահեն կոնցեպտուալ մոդել, որտեղ ռեսուրսային աուդիտը հանդես է գալիս որպես հիմնական ախտորոշիչ և կառավարման գործիք:

Առաջարկվող մոդելը հնարավորություն է տալիս բացահայտել համակարգային անհամապատասխանություններ՝ ներառյալ կոմպետենցիաների պակասը, տեխնոլոգիական անհամապատասխանությունները, ռեսուրսների ոչ արդյունավետ բաշխումը, ինչպես նաև կարգավորող և իրավական պահանջների կատարման խնդիրները: Գիտական նորույթը կայանում է ռեսուրսների կառավարման համակարգում ինստիտուցիոնալ և իրավական գործոնների ներառման մեջ՝ ընդգծելով, որ արդյունավետությունը կախված է ոչ միայն ռեսուրսների առկայությունից, այլ նաև իրավական դաշտի որակից և դրա իրական կիրառությունից: Մոդելը ներառում է հետադարձ կապի մեխանիզմ, որը ապահովում է շարունակական հարմարվողականություն և կայուն զարգացում: Արդյունքները ձևավորում են մեթոդաբանական հիմք՝ արդյունավետության բարձրացման, ռիսկերի նվազեցման, իրավական պահանջների պահպանման և արդյունաբերական ու շինարարական ձեռնարկությունների կայուն զարգացման համար:

Բանալի բառեր՝ ռեսուրսային աուդիտ, արդյունաբերական ձեռնարկություն, շինարարության ոլորտ, ռեսուրսների դիսբալանս, օրենսդրական դաշտ, պահանջների կատարում, թվայնացում, օպտիմալացման մոդել:

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RESOURCE AUDIT–BASED OPTIMIZATION OF INDUSTRIAL ENTERPRISE PERFORMANCE THROUGH MANAGEMENT AND TECHNOLOGICAL INNOVATIONS

ОПТИМИЗАЦИЯ ЭФФЕКТИВНОСТИ ПРОМЫШЛЕННЫХ ПРЕДПРИЯТИЙ НА ОСНОВЕ РЕСУРСНОГО АУДИТА С ИСПОЛЬЗОВАНИЕМ УПРАВЛЕНЧЕСКИХ И ТЕХНОЛОГИЧЕСКИХ ИННОВАЦИЙ

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Рассматривается проблема повышения эффективности промышленных и строительных предприятий в условиях дисбаланса ресурсов, ограничений нормативно-правовой базы и роста технологической сложности. Несмотря на значительное количество исследований в области управления ресурсами, существующие подходы носят фрагментарный характер, рассматривая отдельно кадровый, материально-технический и информационный потенциал, при этом недостаточно учитывается их интеграция и роль исполнения нормативных требований.

Предлагается концептуальная модель оптимизации предприятия, основанная на принятии управленческих решений, в которой ресурсный аудит выступает ключевым инструментом диагностики и управления. Модель позволяет выявлять системные дисбалансы, включая дефицит компетенций, технологические несоответствия, неэффективное распределение ресурсов, а также проблемы нормативного регулирования и их исполнения.

Новизна исследования заключается во включении институционального и правового факторов в систему управления ресурсами, что позволяет учитывать влияние качества нормативной базы и эффективности ее реализации на результаты деятельности предприятия. Модель включает механизм обратной связи, обеспечивающий непрерывную адаптацию и устойчивое развитие.

Полученные результаты формируют методологическую основу для повышения эффективности, снижения рисков, улучшения соблюдения нормативных требований и обеспечения устойчивого развития промышленных и строительных предприятий.

Ключевые слова: ресурсный аудит, промышленное предприятие, строительная отрасль, дисбаланс ресурсов, нормативно-правовая база, исполнение требований цифровизация, оптимизационная модель.

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ELECTRICITY TARIFF DYNAMICS AND THE ECONOMIC DETERMINANTS OF REGIONAL ENERGY COOPERATION

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Abstract

This paper examines the dynamics of electricity tariffs and the economic determinants of regional energy cooperation, with a particular focus on post-Soviet countries and the South Caucasus during the period 2022–2025. The analysis is based on a combined dataset drawn from international sources, including the International Energy Agency (IEA), the World Bank, and global electricity price databases. The methodological framework integrates comparative statistical analysis, time-series evaluation, group-based comparisons, and cross-sectional econometric modeling. Electricity tariff dynamics are analyzed using index-based and relative change indicators, while structural differences in access are assessed through the Electricity

Access Index (EAI), which incorporates overall, urban, and rural electrification rates. To identify the key determinants of electricity access, a multivariate regression model is applied.

The results indicate the emergence of distinct tariff subregions within the post-Soviet space: high-price zones (Baltic countries), medium-price zones (South Caucasus), and low-price zones (Central Asia). Empirical findings reveal that rural electrification is the primary determinant of electricity access, whereas GDP per capita and tariff levels do not exhibit statistically significant effects. Armenia maintains a relatively stable but comparatively high tariff position in the region, largely due to a regulated pricing system and a diversified energy mix. The findings suggest that electricity tariff dynamics are shaped by the combined influence of resource endowment, market structure, regulatory frameworks, and regional integration processes. The paper highlights the importance of targeted tariff policies, infrastructure investments, and cross-border energy cooperation in ensuring energy affordability, efficiency, and long-term energy security.

Keywords: electricity tariffs, energy cooperation, electricity access, post-Soviet countries, South Caucasus, energy economics.

Introduction

Electricity is a fundamental input in modern economies, underpinning production processes, technological progress, and household welfare. As a non-storable good with network characteristics, electricity markets exhibit distinctive structural features, including natural monopoly segments, high fixed costs, and significant regulatory oversight. These characteristics imply that electricity pricing is not solely determined by market forces but emerges from the interaction between resource endowments, market structures, and regulatory regimes.

The cross-country variation in electricity tariffs reflects deep structural heterogeneity. Differences in generation technologies, fuel mix composition, infrastructure quality, and institutional capacity lead to substantial disparities in cost structures and pricing outcomes. Countries endowed with abundant hydropower or fossil fuel resources often exhibit lower marginal costs, whereas economies reliant on imported energy or capital-intensive technologies tend to face higher tariff levels. At the same time, technological progress—particularly the diffusion of renewable energy—has introduced new dynamics into electricity markets by altering cost structures, intermittency patterns, and investment requirements.

From a theoretical perspective, electricity tariff formation can be understood within the framework of regulated market structures. Traditional public utility theory emphasizes cost-of-service regulation and price-setting mechanisms aimed at ensuring cost recovery and system reliability. In contrast, modern regulatory approaches—such as incentive-based regulation and liberalized market designs—seek to enhance efficiency while maintaining affordability and security of supply.

In recent decades, global energy systems have undergone significant transformation driven by decarbonization policies, the expansion of renewable energy sources, and increasing demand pressures. These changes have heightened the complexity of electricity markets, amplifying price volatility and reinforcing the importance of regulatory frameworks in stabilizing tariff dynamics. In this context, regional energy integration has emerged as a critical mechanism for improving efficiency, reducing costs, and enhancing energy security through cross-border electricity trade and infrastructure interconnections.

The post-Soviet region and the South Caucasus provide a particularly relevant empirical setting for analyzing these dynamics. These countries share a common legacy of centrally planned energy systems but have followed divergent paths in market liberalization, regulatory reform, and integration into regional and global energy networks. As a result, the region exhibits pronounced variation in tariff structures, access levels, and institutional arrangements.

Against this background, this study investigates the dynamics of electricity tariffs and the structural determinants of regional energy cooperation in post-Soviet countries and the South Caucasus over the period 2022–2025. The primary objective is to analyze tariff dynamics, assess regional heterogeneity, and identify the key economic and structural factors influencing regional energy cooperation.

Electricity price formation in modern energy economics is increasingly conceptualized as a multi-dimensional process shaped by the interaction of market structure, regulatory design, generation mix, cross-border integration, and technological change. Rather than being determined solely by cost factors or competition, electricity tariffs emerge as equilibrium outcomes within regulated market systems [1]. Empirical evidence suggests that electricity market liberalization does not produce uniform pricing outcomes. Knittel and Roberts [5] demonstrate that price behavior in restructured electricity markets is highly sensitive to market concentration and regulatory oversight. Similarly, Bacchiocchi et al. [1] find that liberalization effects vary significantly across European Union countries. A growing body of literature focuses on the impact of renewable energy on electricity prices. Ballester and Furió [2] show that renewable energy expansion affects both price levels and volatility, while Clò et al. [3] confirm the presence of the merit-order effect, whereby renewable energy reduces wholesale electricity prices. Recent studies emphasize the importance of system flexibility and infrastructure development. Gaffney et al. [4] highlight the need for balancing mechanisms and grid investments, while Joskow [6] underscores the critical role of transmission expansion in achieving efficient energy transitions. Another important dimension concerns the relationship between market integration and electricity prices. Klopčič et al. [17] find that increased cross-border electricity flows can contribute to lower consumer prices, although this effect depends on institutional quality and market maturity. Institutional analyses by the International Energy Agency [8–10; 22] and the European Commission [11–12] indicate that electricity prices remain structurally elevated following the 2022 energy crisis, reflecting persistent cost pressures and structural changes in global energy systems. At the regional level, OECD studies [13–14] highlight that electricity tariff dynamics in the South Caucasus are strongly influenced by regulatory frameworks, state participation, and subsidy mechanisms. In Armenia, sectoral stability is closely linked to regulatory efficiency and infrastructure modernization [15].

Methodology

The methodological framework of this study is based on an integrated approach that combines comparative statistical analysis, time-series examination, group-based comparisons, index and relative calculations, as well as cross-sectional econometric estimation. The primary objective of the research is to analyze electricity tariff dynamics, identify regional disparities, assess structural inequalities in electricity access, and examine the economic determinants of regional energy cooperation.

The subject of the study is the temporal variation of final electricity tariffs across countries and country groups, as well as the structural characteristics of electricity access levels. Particular emphasis is placed on post-Soviet countries, the South Caucasus, and neighboring regions, alongside a broader global comparative sample that enables the evaluation of different pricing and access models.

The empirical foundation of the study is constructed through the integration of international and national statistical sources, including data from the World Bank [16], the International Renewable Energy Agency (IRENA) [8].

The dataset includes final electricity tariff indicators across countries for the period 2022–2025, overall electricity access rates, urban and rural electrification levels, GDP per capita data, as well as comparative averages for selected countries and regional groupings.

To ensure cross-country comparability, all tariff indicators are standardized in U.S. dollars per kilowatt-hour (USD/kWh). Electricity access indicators are expressed in percentage terms, while GDP per capita is measured in current U.S. dollars. This standardization enables consistent temporal and cross-sectional analysis.

To ensure cross-country comparability, all tariff indicators are standardized in U.S. dollars per kWh (USD/kWh). Electricity access indicators are expressed in percentage terms, while GDP per capita is measured in current U.S. dollars. This standardization enables consistent temporal and cross-sectional analysis.

Descriptive statistics of the main variables used in the study are presented in Table 1.

Table 1

Descriptive Statistics of the Main Variables Used in the Study

Variable	Mean	Min	Max	Std.Dev
Access (%)	90.5	14	100	19.62
Rural access (%)	85.38	3.4	100	28.64
Price (USD/kWh)	0.167	0.006	0.465	0.109
GDP per capita	23635	357	188055	31772

Table 1 indicates that the average level of electricity access is 90.5%, although significant cross-country variation is observed.

The correlation between the variables is presented in Table 2.

Table 2

Correlation Matrix of the Main Variables Used in the Study

	Access	GDP	Price	Rural
Access	1	0.34	0.19	0.95

GDP	0.34	1	0.55	0.35
Price	0.19	0.55	1	0.2
Rural	0.95	0.35	0.2	1

The strongest relationship is observed between overall and rural electricity access (0.95), confirming the critical role of infrastructure in shaping access outcomes.

Research Design and Analytical Framework

The analysis is conducted in five sequential stages.

In the first stage, the temporal dynamics of electricity tariffs are examined to identify trends of increase, decrease, or relative stability over the period 2022–2025.

In the second stage, a cross-country and regional comparative analysis is performed to determine the formation of high-, medium-, and low-tariff zones across different countries and regional groupings.

In the third stage, structural inequalities in electricity access are assessed through the comparison of overall, urban, and rural electrification indicators.

In the fourth stage, the stages of electrification development and the main patterns of structural disparities in access are evaluated.

In the fifth stage, an econometric estimation is conducted to identify the key economic and structural determinants of overall electricity access.

Time-Series Analysis

To evaluate electricity tariff dynamics, a comparative time-series approach is applied. For each country, electricity tariffs are treated as a time-dependent variable:

$$P_{it} = \alpha_i + \beta_i t + \varepsilon_{it} \,, \tag{1}$$

where: P_{it} — *electricity tariff in country i at time t*, α_i— country-specific baseline (intercept) level, $\beta_i t$ — coefficient capturing the time trend, ε_{it}— stochastic error term.

The relative change in electricity prices is calculated using the following formula:

$$\Delta \mathrm{P}_{\boldsymbol{it}} = \frac{P_{it} - P_{it-1}}{P_{it-1}} \times 100. \tag{2}$$

This indicator allows for the assessment of the percentage change in electricity tariffs relative to the previous period. The cumulative change relative to the base period is measured using an index-based approach:

$$I_{it} = \frac{P_{it}}{P_{i0}} \times 100 \,, \tag{3}$$

where P_{i0} denotes the electricity tariff in the base period.

Cross-Sectional and Group Comparative Analysis

To assess cross-country differences in electricity tariffs, a relative difference indicator is employed:

$$RD_{ij,t} = \frac{P_{it} - P_{jt}}{P_{jt}} \times 100 \,, \tag{4}$$

where $RD_{ij,t}$ indicates the extent to which the electricity tariff in country *i* is higher or lower relative to country *j* at time *t*. This approach is particularly useful for assessing Armenia’s tariff position in comparison with neighboring countries and post-Soviet economies.

To identify regional and institutional differences, group averages are also calculated:

$$\bar{P}_{g,t} = \frac{1}{n_g} \sum_{i=1}^{n_g} P_{it} \ , \tag{5}$$

where $\bar{P}_{g,t}$ denotes the average electricity tariff for group g at time t, and N_g represents the number of countries included in the respective group. This approach is applied to compare the European Union (EU), the Eurasian Economic Union (EAEU), the Commonwealth of Independent States (CIS), the South Caucasus, post-Soviet countries, and the global average.

To assess the degree of group homogeneity, the standard deviation is also employed:

$$\sigma_{g,t} = \sqrt{\frac{1}{n_g} \sum_{i=1}^{n_g} (P_{it} - \bar{P}_{g,t})^2}. \tag{6}$$

Assessment of Structural Inequality in Electricity Access

To evaluate structural differences in electricity access, indicators of overall, urban, and rural electrification are employed. The disparity between urban and rural access is defined as a measure of structural inequality:

$$Gap_i = U_i - R_i \ , \tag{7}$$

where: Gap_i — the urban–rural electrification gap in country i, U_i — electricity access rate of the urban population, R_i— electricity access rate of the rural population.

This indicator enables the identification of countries where the spatial distribution of energy infrastructure is most uneven.

In addition, a composite electrification index is calculated:

$$EAI_i = 0.5T_i + 0.25U_i + 0.25R_i, \tag{8}$$

where: EAI_i — Electricity Access Index, T_i — overall electricity access rate, U_i — urban electricity access rate, R_i — rural electricity access rate.

This index allows for the classification of countries according to their overall level of electrification development.

Classification of Electrification Development Stages

In this study, countries are classified into three stages based on the level of overall electricity access:

- Stage I — Energy Poverty: when access is below 50%,
- Stage II — Energy Transition: when access ranges between 50% and 95%,
- Stage III — Universal Access: when access exceeds 95%.

This classification enables a comparative assessment of countries' positions along the electrification development spectrum and helps identify those where the primary challenge remains at the initial or intermediate stages of electrification.

Econometric Estimation Approach

To identify the economic and structural determinants of electricity access, a cross-sectional multivariate regression model is employed. The dependent variable is the overall electricity access rate, while the explanatory variables include GDP per capita, electricity tariffs, and rural electricity access.

The econometric model is specified as follows:

$$Access_i = \alpha + \beta_1 GDP_{pci} + \beta_2 Price_i + \beta_3 RuralAccess_i + \varepsilon_i, \tag{9}$$

where: $Access_i$— *overall electricity access in country i*, GDP_{pci} — GDP per capita, $Price_i$— electricity tariff level, $RuralAccess_i$ — electricity access rate of the rural population, ε_i—

stochastic error term.

The purpose of the model is to identify the key factors driving variation in national electrification levels

From a theoretical perspective, it is expected that GDP per capita and rural electricity access exert a positive effect on overall access, while the impact of electricity tariffs may be ambiguous. Specifically, tariffs may reflect either affordability constraints that limit access or, alternatively, more advanced and investment-intensive energy systems characterized by higher cost structures.

To evaluate the economic foundations of regional energy cooperation, a simple price differential indicator is also employed:

$$TI_{ij,t} = P_{j,t} - P_{i,t} \,, \tag{10}$$

where $TI_{ij,t}$ reflects the electricity tariff gap between countries i and j at time t. If this difference is positive, it theoretically creates conditions under which the country with lower electricity tariffs may gain a competitive advantage in electricity exports, the location of energy-intensive production, or mutually beneficial energy cooperation.

At the same time, this indicator is interpreted with caution, as actual cooperation outcomes depend not only on price differentials but also on the availability of cross-border transmission infrastructure, technical capacity constraints, political relations, and the regulatory environment.The results of the econometric model estimation are presented in Table 3.

Table 3

Econometric Estimation Results of the Determinants of Electricity Access

Variable	Coefficient	Std.Error	p-value
GDP per capita	0.0000036	0.000022	0.869
Electricity price	0.309	6.143	0.960
Rural access	0.649***	0.021	0.000
Constant	34.94	1.91	0.000
R-squared	0.902		

Note: *** p<0.01, ** p<0.05, * p<0.10

The results indicate that rural electrification has the most significant effect on electricity access (0.649, $p < 0.01$). At the same time, GDP per capita and electricity tariffs are not statistically significant. The model exhibits strong explanatory power ($R^2 = 0.902$).

Fig. 1 Relationship Between GDP per Capita and Electricity Access

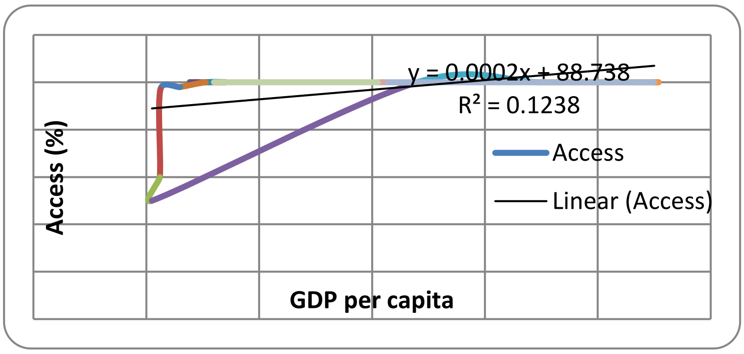


Fig. 1 indicates a weak positive relationship between GDP per capita and electricity access. However, this relationship is not statistically significant, which is consistent with the econometric estimation results.

To ensure the reliability of the model estimation, a series of diagnostic tests were conducted. Multicollinearity was assessed through correlation analysis and the Variance Inflation Factor (VIF). The results indicate that VIF values remain within acceptable thresholds, suggesting the absence of significant collinearity among the explanatory variables.

In addition, heteroskedasticity was tested using the Breusch–Pagan test. The findings suggest that the variance of the residuals does not violate the homoskedasticity assumption. Where necessary, robust standard errors were applied to improve the reliability of the estimates.

To verify the stability of the results, additional estimations were performed using alternative model specifications. In particular, logarithmic transformations of the variables were applied to account for potential non-linear relationships. The results preserve the signs and statistical significance of the main coefficients, indicating the robustness of the estimates.

Furthermore, the model was estimated using different combinations of explanatory variables to test the sensitivity of the results to sample composition and variable structure. The findings show that the main conclusions remain unchanged, confirming the overall validity of the model.

The selected econometric model is grounded in the theoretical frameworks of energy economics and development economics, according to which electricity access is determined by both economic development and structural factors. GDP per capita reflects the population’s purchasing power and investment capacity, while rural electrification captures the spatial development of energy infrastructure. Electricity tariffs are included as an indicator of affordability and cost conditions, which may either constrain consumption or reflect the level of system development.

Thus, the model integrates economic, structural, and institutional factors, providing a comprehensive assessment of the determinants of electricity access.

Limitations

The methodology of this study is subject to several limitations. First, electricity tariffs may be reported for different consumer categories across countries, which in some cases limits direct comparability.

Second, tariff structures may include taxes, subsidies, or social adjustments in certain countries, while in others such components are absent or treated differently.

Third, the econometric analysis of electricity access is cross-sectional in nature and primarily captures structural associations rather than strict causal relationships.

Fourth, the assessment of the economic preconditions for regional energy cooperation cannot be reduced solely to price differentials and requires additional technical and institutional data, including transmission capacity, infrastructure connectivity, and regulatory harmonization.

Moreover, the use of cross-sectional data inherently constrains the identification of causal relationships.

To address potential limitations, it should be noted that the model is cross-sectional and may be affected by structural heterogeneity across countries. The relationship between income and electricity access may be non-linear due to saturation effects, while electricity tariffs may reflect both affordability constraints and cost-recovery mechanisms.

Methodological Conclusion

Overall, the methodological framework of this study integrates descriptive statistics, time-series analysis, index and relative calculations, structural assessment of electricity access, and cross-sectional econometric modeling.

Such a combined approach enables not only the characterization of electricity tariff dynamics and regional disparities, but also the identification of the structural factors that shape electrification levels and the economic potential for regional energy cooperation.

Results and Discussion

In recent years, electricity price dynamics have been shaped by both structural transformations in global energy markets and internal changes within national energy systems. Empirical evidence suggests that in a number of advanced economies, price fluctuations are driven by a combination of fuel market volatility, increasing penetration of renewable energy sources, and network constraints.

More specifically, available evidence indicates that increases in wholesale electricity prices are often driven by changes in the generation mix and capacity constraints, while the expansion of renewable energy sources contributes to higher price volatility. These developments reflect a dual dynamic in energy markets: a long-term transition toward decarbonization alongside short-term price instability.

At the same time, the experience of European countries demonstrates that a high-tariff environment can adversely affect industrial competitiveness, particularly in energy-intensive sectors. Comparative data show that in certain economies, electricity prices significantly exceed international averages, thereby constraining production activity and reducing investment attractiveness.

At the global level, electricity demand growth continues to be driven by electrification, industrial expansion, and digitalization processes. In this context, developing economies act as the primary drivers of demand, while in advanced economies electricity price dynamics tend to be more sensitive to policy measures and structural changes in market design.

Meanwhile, external shocks continue to exert a substantial influence on electricity prices. Disruptions in energy supply chains and geopolitical tensions can lead to sharp price increases, especially in regions dependent on imported fuels. This underscores the importance of energy security and diversification as key stabilizing factors.

For instance, in Australia, wholesale electricity prices increased sharply in the fourth quarter of 2024 due to declining coal production and grid constraints [18]. At the same time, solar generation reached record levels, highlighting the growing variability of electricity markets [19].

In the United Kingdom, high electricity prices became a major challenge for businesses in 2023, negatively affecting competitiveness in energy-intensive sectors [20].

Reduced wind power generation in Germany led to increased reliance on fossil fuels and rising electricity prices across Europe in early 2025 [21].

According to the International Energy Agency, global electricity demand is expected to grow at an average annual rate of approximately 3.4% during 2023–2026, driven primarily by emerging economies [22]. In contrast, wholesale electricity prices in the United States declined in 2024 due to increased natural gas availability and renewable energy expansion [23].

Electricity prices are also influenced by global shocks, particularly those affecting hydrocarbon fuel markets. The geopolitical disruptions associated with the Russia–Ukraine conflict in 2022 led to significant increases in electricity prices worldwide, especially in Europe.

According to Cable.co.uk data, electricity prices in 2024 were highest in Bermuda (USD 0.458 per kWh), while Armenia's electricity price remained relatively low at approximately USD 0.112 per kWh [24].

Statista data for March 2024 indicate that electricity prices in European countries such as Italy (USD 0.43 per kWh), Ireland (USD 0.41), and Denmark (USD 0.36) are among the highest globally [25].

According to GlobalPetrolPrices data, the global average electricity price in the fourth quarter of 2024 was approximately USD 0.150 per kWh for households and USD 0.146 for businesses. Europe remains the highest-cost region, while Asia records the lowest average prices [26].

European Commission data show that the average electricity price for households in the EU reached €0.2889 per kWh in the first half of 2024, with the highest prices observed in Germany, Ireland, and Denmark [12].

According to International Energy Agency datasets, electricity price monitoring now covers more than 140 countries and provides detailed insights into pricing structures, including tax components and regional variations [9].

Elevated electricity prices may also slow down the transition to green technologies, as higher energy costs reduce investment incentives in renewable energy systems [19, 20].

Table 4

Electricity Tariffs and Their Dynamics in Former Soviet Union Countries, 2022–2025 (USD/kWh)

Country	**2025**	**2024**	**2023**	**2022**	**2024/2022,%**
Estonia	0.286	0.291	0.319	0.393	74.0
Lithuania	0.271	0.267	0.36	0.502	53.2
Latvia	0.28	0.256	0.295	0.317	80.8
Moldova	0.17	0.138	0.115	0.147	93.9
Armenia	0.111	0.112	0.103	0.104	107.7
Belarus	0.083	0.075	0.092	0.091	82.4
Ukraine	0.08	0.064	0.039	0.039	164.1
Georgia	0.067	0.062	0.076	0.077	80.5
Russia	0.065	0.058	0.064	0.059	98.3
Kazakhstan	0.055	0.05	0.045	0.045	111.1
Azerbaijan	0.047	0.047	0.047	0.047	100.0
Tajikistan	-	0.045	0.049	0.051	88.2
Turkmenistan	-	0.03	0.025	0.024	125.0
Uzbekistan	0.035	0.023	0.026	0.026	88.5
Kyrgyzstan	0.014	0.013	0.01	0.01	130.0

Note: *The table presents the average final electricity tariffs for households in former Soviet Union countries, expressed in USD per kWh. The data are reported for September 2022, March 2023, and March 2024, allowing for an assessment of electricity tariff dynamics across the region. The indicator "2024/2022, %" reflects the relative change in tariffs, calculated as the ratio of March 2024 values to those of September 2022. Data for 2025 are presented based on available statistical sources and estimates. For Tajikistan and Turkmenistan, data for 2025 are not available due to limitations in statistical reporting and data availability in the relevant sources.*

Source: *Compiled by the author based on data from Global Petrol Prices, Cable.co.uk. Electricity prices and pricing in 230 countries. Retrieved from https://www.globalpetrolprices.com/electricity_prices/*

Electricity price and production data were collected from multiple sources, including Global Petrol Prices (Electricity Prices), Cable.co.uk (Electricity Prices in 230 Countries), the International Energy Agency (IEA, Global Electricity Statistics), the International Renewable Energy Agency (IRENA, Electricity and Energy Development in the South Caucasus), the World Bank (Electricity Production and Consumption by Country), the Statistical Committee of the Republic of Armenia (Electricity Production and Energy Statistics of Armenia).

(USD/kWh)

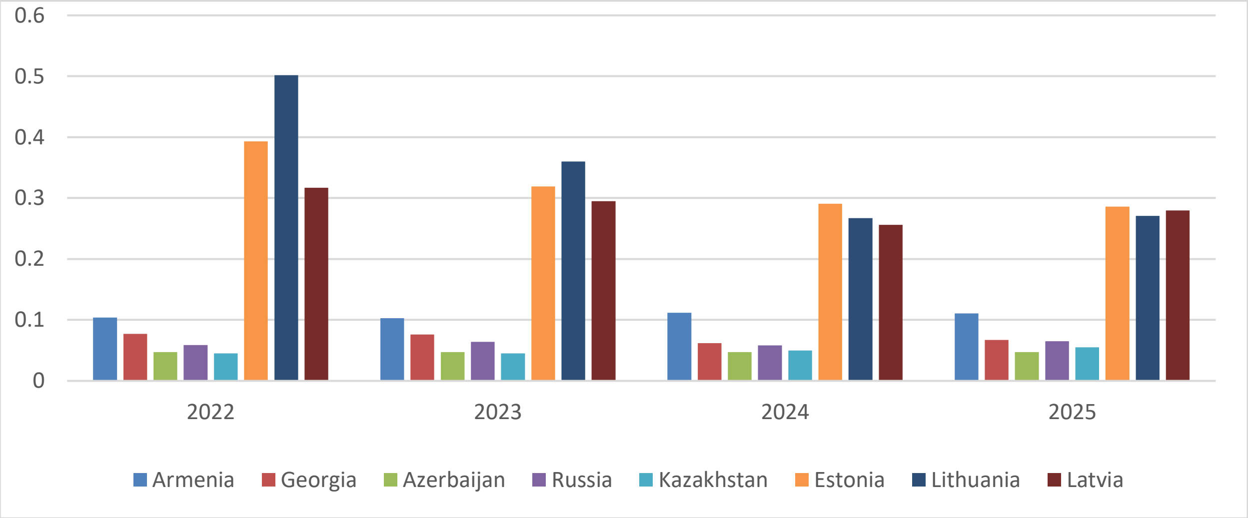


Fig. 2 Comparative Electricity Tariffs in Selected Countries, 2022–2025

The presented data indicate that electricity tariff dynamics in former Soviet Union countries during 2022–2025 have been heterogeneous, reflecting substantial differences in energy development trajectories, regulatory frameworks, and market structures across the region. Although these countries historically operated within a unified economic system, the post-Soviet period has been characterized by divergent institutional transformations in energy sectors, varying subsidy policies, differing degrees of integration into international markets, and unequal resource endowments. These factors have resulted in the emergence of a multi-polar tariff structure.

As a consequence, at least three distinct tariff subregions can be identified within the former Soviet space: the Baltic states, the South Caucasus, and Central Asia, each characterized by its own economic logic of price formation.

First, the highest tariff levels continue to be observed in the Baltic countries—Estonia, Lithuania, and Latvia. Although a decline in tariffs was recorded in 2024 compared to 2022, data for 2025 suggest the emergence of a stabilization phase, without a significant further decrease. Specifically, in 2025 electricity tariffs reached USD 0.286 per kWh in Estonia, USD 0.271 in Lithuania, and USD 0.280 in Latvia. These figures reflect not only a persistently high price environment but also the deep integration of these countries into European energy markets. The elevated price levels in 2022 were largely driven by the European energy crisis, volatility in natural gas markets, and accelerated efforts to reduce energy dependence on Russia. Therefore, the relative stabilization observed in 2024–2025 should not be interpreted as a return to lower, pre-crisis price levels, but rather as the establishment of a new equilibrium at a comparatively higher price range. In other words, in the case of the Baltic states, the evidence points to a «new normal» of elevated electricity prices rather than a full price correction.

In contrast, the South Caucasus exhibits a more moderate and relatively stable tariff environment. Armenia, Georgia, and Azerbaijan are characterized by lower electricity tariffs, although notable differences persist among them. In Armenia, electricity tariffs in 2025 amounted to USD 0.111 per kWh, showing minimal deviation from both 2024 and 2022 levels. This indicates a relatively stable tariff policy throughout the observed period, with only limited fluctuations. Such stability can be attributed to the country's diversified energy mix—combining nuclear, thermal, and hydropower sources—as well as the continued presence of a regulated tariff-setting system.

In Georgia, electricity tariffs reached USD 0.067 per kWh in 2025, reflecting a moderate increase compared to 2024 while remaining at a relatively low level. This may be explained by the country's substantial hydropower potential, alongside emerging cost pressures within the domestic energy system.

In Azerbaijan, by contrast, tariffs remained effectively unchanged over the period 2022–2025 at approximately USD 0.047 per kWh. This stability reflects a state-controlled tariff regime, supported by abundant oil and gas resources, which allows the country to maintain low electricity prices with relatively limited exposure to international price fluctuations.

In Central Asian countries, the lowest tariff zone continues to prevail, primarily driven by two key factors: the relative abundance of natural resources and tariff policies that are heavily subsidized for social and political purposes. This group is particularly represented by Kyrgyzstan, Uzbekistan, Tajikistan, and Turkmenistan, where electricity tariffs remain significantly lower not only compared to the Baltic states but also to the South Caucasus.

However, these low tariff levels do not necessarily imply efficiency or market equilibrium. On the contrary, they often reflect underlying structural issues such as cross-subsidization, state financial support, underinvestment, and infrastructure depreciation risks.

In Kazakhstan, electricity tariffs reached USD 0.055 per kWh in 2025, continuing the upward trend observed since 2024. In Kyrgyzstan, tariffs stood at USD 0.014 per kWh, also maintaining a gradual upward trajectory. Uzbekistan similarly recorded an increase in 2025, with tariffs rising from USD 0.023 to USD 0.035 per kWh. These developments suggest that even traditionally low-tariff systems are subject to gradual adjustments over time, driven by rising production, distribution, and investment costs, as well as the progressive rationalization of subsidies.

At the same time, the absence of 2025 data for Tajikistan and Turkmenistan limits a comprehensive assessment of their recent dynamics. Nevertheless, available data for 2022–2024 indicate that these countries have also maintained relatively low tariff positions.

The cases of Moldova and Ukraine are particularly illustrative of high energy vulnerability and the impact of external shocks.

In Moldova, electricity tariffs reached USD 0.170 per kWh in 2025, exceeding not only those of most South Caucasus and Central Asian countries but also showing a significant increase compared to 2024 levels. This can be explained by high dependence on energy imports, constraints related to energy security, and structural fragility of the domestic energy system.

In Ukraine, the situation is even more complex. Electricity tariffs increased to USD 0.080 per kWh in 2025, compared to USD 0.064 in 2024 and only USD 0.039 in 2022. Although the absolute level remains moderate relative to some countries, the magnitude of the increase reflects deep systemic disruptions.

Under conditions of ongoing conflict, damage to energy infrastructure, loss of generation capacity, disruptions in supply chains, and additional reconstruction costs have necessitated continuous tariff adjustments. The Ukrainian case highlights an important analytical distinction: low absolute tariff levels do not necessarily imply system stability, and relative dynamics may provide a more accurate reflection of structural stress.

Russia and Belarus represent relatively stable electricity pricing systems, albeit based on different economic logics.

In Russia, electricity tariffs reached USD 0.065 per kWh in 2025, showing a modest increase compared to 2024 while remaining within a relatively low and controlled range. This largely reflects the availability of abundant domestic energy resources and relatively low-cost generation.

In Belarus, tariffs increased to USD 0.083 per kWh in 2025, reversing the decline observed in 2024 and indicating a moderate upward adjustment.

Both cases illustrate that domestic resource availability, centralized state control, and direct or indirect tariff regulation continue to mitigate the impact of global energy market fluctuations on domestic price formation. However, even in these systems, the data for 2025 suggest the emergence of gradual price adjustments.

Synthesis and Policy Implications

The inclusion of 2025 data provides an additional opportunity to assess not only post-crisis recovery but also the direction of emerging tariff trends. While the Baltic countries exhibit relative stabilization in 2025, with only minor fluctuations, a clearer upward trajectory is observed in several other countries. In particular, Moldova, Belarus, Ukraine, Georgia, Russia, Kazakhstan, Uzbekistan, and Kyrgyzstan recorded higher tariff levels in 2025 compared to 2024. This suggests that following the initial shock phase of 2022, the region has entered a second stage of tariff adjustment. In this phase, price dynamics are driven less by direct crisis-related effects and more by underlying structural factors, including rising production and distribution costs, investment requirements, exchange rate fluctuations, and regulatory adjustments. In this context, 2025 can be interpreted as a transitional period, marking the shift from crisis-driven adaptation toward a new structural price equilibrium.

At the same time, the 2025 data indicate that tariff convergence across the post-Soviet space is not occurring. On the contrary, in some subregions, disparities are either persisting or even widening, reflecting divergent development paths and institutional configurations.

One of the key findings of the analysis is that electricity tariffs in the former Soviet Union cannot be explained solely by resource endowments. While the availability of energy resources constitutes an important precondition, tariff outcomes are equally shaped by institutional arrangements, public policy priorities, subsidy mechanisms, social protection systems, the degree of external integration, and the scale of infrastructure investment needs.

Thus, even countries with similar resource bases may exhibit significantly different tariff levels depending on governance quality and regulatory models. The 2025 data further emphasize that, in the long run, the financial capacity to modernize energy systems becomes as important as resource availability itself.

From a policy perspective, the findings highlight the need for countries in the region to balance three key objectives: social affordability, the financial viability of energy companies, and the long-term modernization of infrastructure.

Excessively low tariffs may ensure short-term social acceptability but often constrain investment capacity and exacerbate infrastructure degradation over time. Conversely, rapid and substantial tariff increases may intensify energy poverty and social inequality, particularly among low-income households.

Therefore, effective tariff policy should not rely solely on market signals but must also incorporate targeted social protection, efficient subsidy design, and mechanisms to promote energy efficiency. The observed trends in 2025 suggest that many countries are currently engaged in adjusting this balance, which has become a central driver of tariff reforms.

Table 5

Comparative Electricity Tariff Levels in the South Caucasus and Neighboring Countries, 2022–2025

Country	**2025**	**2024**	**2023**	**2022**	**2025/2022,%**
Armenia	0.111	0.112	0.103	0.104	106.7
Georgia	0.067	0.062	0.076	0.077	87.0
Russia	0.065	0.058	0.064	0.059	110.2
Turkey	0.067	0.048	0.077	0.073	91.8
Azerbaijan	0.047	0.047	0.047	0.047	100.0
Iran	0.003	0.002	0.005	0.002	150.0

Source: *Compiled by the author based on data from Global Petrol Prices, Cable.co.uk, Electricity prices and pricing in 230 countries. Retrieved from* https://www.globalpetrolprices.com/electricity_prices/

Electricity price and production data were collected from multiple sources, including Global Petrol Prices (Electricity Prices), Cable.co.uk (Electricity Prices in 230 Countries), the International Energy Agency (IEA, Global Electricity Statistics), the International Renewable Energy Agency (IRENA, Electricity and Energy Development in the South Caucasus), the World Bank (Electricity Production and Consumption by Country), the Statistical Committee of the Republic of Armenia (Electricity Production and Energy Statistics of Armenia).

In conclusion, the comparative analysis of electricity tariffs in former Soviet Union countries over the period 2022–2025 reveals pronounced regional differentiation and confirms that the post-Soviet energy space no longer functions as a unified tariff zone. The Baltic countries represent a Europeanized, high-price, and integrated model; the South Caucasus constitutes an intermediate zone characterized by relative stability and mixed energy structures; while Central Asia reflects a low-tariff system often sustained by subsidies.

The incorporation of 2025 data further demonstrates that a new phase of tariff adjustment is underway in several countries, driven not only by the aftermath of external shocks but also by the accumulation of internal structural challenges.

This differentiation provides an important methodological foundation for future research, particularly when electricity tariffs are considered not merely as price indicators, but as broader measures of economic security, social accessibility, and the effectiveness of energy policy.

Comparative Analysis of Electricity Tariffs in the South Caucasus and Neighboring Countries

The analysis of the presented data indicates that electricity tariff levels in the South Caucasus and neighboring countries during 2022–2025 have been shaped by diverse economic and institutional conditions, reflecting the structural characteristics of regional energy markets. Although these countries are located within the same geographical region and, in some cases, share interconnected energy systems, their tariff policies and pricing mechanisms differ substantially due to variations in resource endowments, regulatory frameworks, and energy system organization.

The data show that among the countries considered, the highest electricity tariffs are observed in Armenia. In 2025, the tariff reached USD 0.111 per kWh, remaining virtually unchanged from 2024 (USD 0.112) and recording a modest increase compared to 2022 (106.7%). This indicates that electricity tariffs in Armenia have remained relatively stable over the analyzed period. Such stability can be attributed to the structure of the country’s energy system, which combines nuclear, thermal, and hydropower generation, as well as to the presence of regulated tariff-setting mechanisms aimed at maintaining social stability.

In Georgia, electricity tariffs exhibit a declining trend over the period under consideration. While tariffs stood at USD 0.077 per kWh in 2022, they decreased to USD 0.067 per kWh by 2025 (87.0%). This development may be associated with the active utilization of the country’s hydropower potential and the significant share of renewable energy sources in its generation mix, which in some cases allows for maintaining relatively competitive tariff levels.

In Russia, electricity tariffs remain relatively low but show a moderate upward trend. In 2025, tariffs reached USD 0.065 per kWh, exceeding the 2022 level (110.2%). This increase may reflect gradual growth in production and distribution costs, as well as the need for infrastructure modernization. At the same time, the country’s abundant energy resources and extensive generation capacity continue to support one of the lower tariff environments in the region.

In Turkey, electricity tariffs display a more volatile dynamic. Tariffs increased to USD 0.077 per kWh in 2023, then declined to USD 0.048 per kWh in 2024, before rising again to

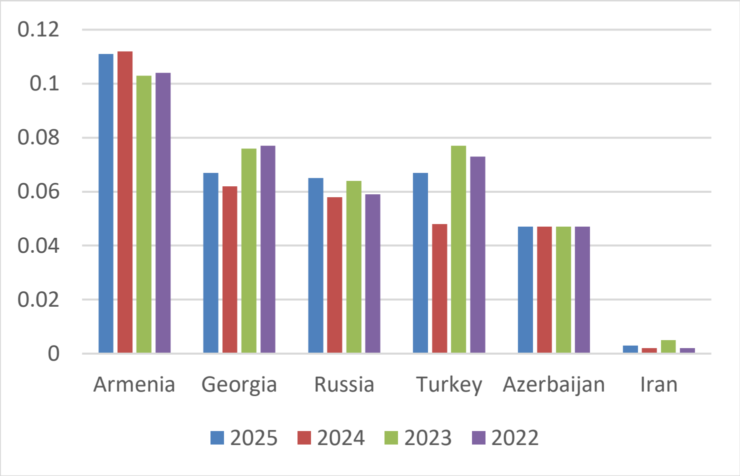
USD 0.067 per kWh in 2025. Overall, the 2025 level remains slightly below that of 2022 (91.8%). Such fluctuations are largely driven by the structure of the energy market, dependence on imported energy resources, exchange rate volatility, and regulatory policies.

In Azerbaijan, electricity tariffs remained unchanged throughout the entire period at approximately USD 0.047 per kWh. This stability reflects a highly controlled energy pricing system, largely supported by abundant oil and gas resources and state subsidies. The availability of domestic energy resources allows the country to maintain relatively low and stable tariffs while minimizing exposure to fluctuations in international energy markets.

In Iran, electricity tariffs are the lowest among the countries considered. In 2025, the tariff amounted to only USD 0.003 per kWh, which, despite representing a significant increase compared to 2022 (150.0%), remains exceptionally low by international standards.

This situation is largely driven by extensive state subsidies and the country's abundant energy resources. However, such extremely low tariff levels may generate efficiency-related challenges, including excessive energy consumption and constraints on investment in the energy sector.

Fig. 3 Comparative Average Electricity Prices Across Country Groups (USD/kWh), 2022–2025



Electricity tariff formation in the region depends on a set of interrelated factors, including the availability of domestic energy resources, government regulatory policies, market structure, and the level of technological development of energy systems.

Table 6

Comparative Levels and Dynamics of Electricity Tariffs Across Country Groups, 2022–2025 (USD/kWh)

Country Groupings	Electricity Price (USD/kWh), 2025	Electricity Price (USD/kWh), 2024	Electricity Price (USD/kWh), 2023	Electricity Price (USD/kWh), 2022	2025/2022,%
Top (15)	0.021	0.012	0.019	0.017	123.5
Armenia and Neighboring Countries (5)	0.059	0.054	0.062	0.061	96.7
EAEU (5)	0.066	0.062	0.063	0.062	106.5
CIS (9)	0.073	0.065	0.063	0.066	110.6
World (All Countries)	0.159	0.157	0.152	0.163	97.5
Central and Southern Europe (11)	0.231	0.233	0.263	0.295	78.3
OECD Average (34)	0.243	0.242	0.257	0.298	81.5
EU (27)	0.27	0.267	0.296	0.353	76.5
Worst (15)	0.384	0.389	0.383	0.421	91.2

Note: *The table presents the average final electricity tariffs for different country groups, expressed in USD per kWh. The data are reported for September 2022, March 2023, March 2024, and March 2025, allowing for an assessment of temporal trends in electricity prices across various regional and institutional groupings.The indicator "2025/2022, %" reflects the relative change in tariffs, calculated as the ratio of 2025 values to those of 2022. The groups "Best (15)" and "Worst (15)" represent the average tariff levels of countries with the lowest and highest electricity prices, respectively, within the sample. The "OECD average" is calculated based on the mean value of OECD member countries included in the dataset (34 countries). The groups "EU (27)" and "Central and Southern Europe (11)" reflect the average levels for the respective regional economic groupings. The "World" row represents the average value across all countries included in the dataset.*
Source: Authors' calculations based on international electricity price databases (Global Electricity Price Database, World Bank energy statistics, and other international statistical sources).

A comparative analysis of the South Caucasus and neighboring countries indicates that in resource-rich or heavily subsidized economies, electricity tariffs are typically maintained at lower levels, whereas in countries dependent on energy imports or characterized by more diversified energy systems, tariffs tend to be relatively higher. This distinction is particularly important for the design of regional energy cooperation and energy security policies, as electricity tariffs serve not only as indicators of economic efficiency, but also as key measures of social affordability and energy system resilience.

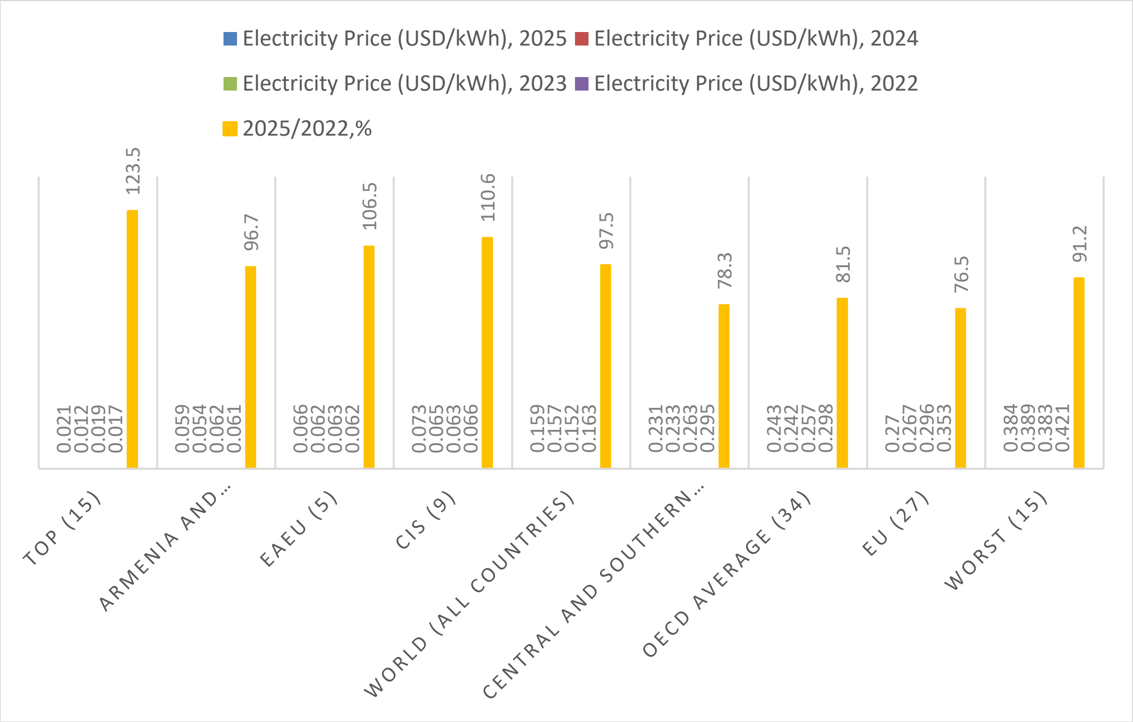


Fig. 4 Comparative Average Electricity Prices Across Country Groups (USD/kWh), 2022–2025

The analysis of the data presented in Table 6 (Fig. 4) indicates that electricity tariff levels across different country groups during 2022–2025 have been shaped by distinct economic and institutional conditions. The observed dynamics reflect both global energy market transformations and the structural characteristics of regional energy systems. At the same time, significant tariff disparities persist across country groups, driven by differences in resource availability, regulatory frameworks, market organization, and the level of energy infrastructure development.

The data show that the lowest tariff levels are observed in the “Top (15)” group, where the average electricity price reached USD 0.021 per kWh in 2025. Despite remaining relatively low, this value significantly exceeds the 2022 level (123.5%), indicating the presence of inflationary pressures even in the lowest-cost countries. These increases may be attributed to rising production costs, volatility in global energy markets, and growing infrastructure investment requirements.

In the group of South Caucasus and neighboring countries, tariff levels remain at a moderate range. The average electricity price in the “Armenia and Neighboring Countries (5)” group reached USD 0.059 per kWh in 2025, slightly below the 2022 level (96.7%). This suggests relatively stable tariff dynamics, likely supported by regulatory mechanisms and the region’s partial access to domestic energy resources.

In the Eurasian Economic Union (EAEU), electricity tariffs also remain relatively low, although a moderate increase is observed. In 2025, the average tariff reached USD 0.066 per kWh, exceeding the 2022 level (106.5%). This trend may reflect infrastructure modernization needs, rising production and distribution costs, and gradual adjustments in subsidy policies. A similar pattern is observed in the Commonwealth of Independent States (CIS), where the average tariff reached USD 0.073 per kWh in 2025 (110.6% relative to 2022).

At the global level, electricity prices remained relatively stable over the period. In 2025, the global average stood at USD 0.159 per kWh, closely aligned with the 2022 level (97.5%). This suggests that, following the 2022 energy crisis, global energy markets have undergone partial rebalancing and price stabilization. However, significant regional differences persist, reflecting structural variations in energy systems and market organization.

Higher tariff levels are observed in European country groups. In Central and Southern Europe, the average electricity price reached USD 0.231 per kWh in 2025, while in the European Union (EU) it rose to USD 0.270 per kWh. Despite these high levels, a declining trend is observed compared to 2022 (78.3% and 76.5%, respectively), reflecting the impact of policy interventions and market adjustments implemented after the energy crisis.

In OECD countries, the average electricity price reached USD 0.243 per kWh in 2025, also significantly lower than in 2022 (81.5%). This indicates that developed economies have been able to partially mitigate the effects of the energy crisis through effective energy policies and regulatory mechanisms.

At the opposite end, the “Worst (15)” group continues to exhibit the highest electricity tariffs, with an average of USD 0.384 per kWh in 2025. Although slightly lower than in 2022 (91.2%), these high price levels are typically associated with dependence on imported energy resources, limited generation capacity, and structural inefficiencies in market design.

Overall, the comparative analysis demonstrates that electricity tariff formation across country groups is determined by a complex interplay of factors, including resource endowments, regulatory policies, infrastructure development, and the degree of market integration. While some degree of price stabilization has occurred following the global energy shock of 2022, tariff disparities across regions remain pronounced.

These findings are particularly relevant for the assessment of regional energy cooperation, energy security, and the effectiveness of energy policy, as electricity tariffs serve not only as indicators of economic efficiency but also as key measures of social affordability and systemic resilience.

Structural Inequality in Electricity Access and Empirical Assessment

A comparative analysis of electricity tariffs cannot be considered complete without examining the structural dimension of access, as relatively low tariff levels do not necessarily imply universal energy inclusion. In this context, electricity access serves not only as an indicator of social welfare, but also as a key measure of infrastructure development, spatial equity, and economic capacity. Therefore, a joint analysis of tariffs and access provides a more comprehensive understanding of the development levels of global and regional energy systems.

Quantitative analysis of global data shows that the average level of overall electricity access across the observed countries is approximately 87%, while access for the urban population exceeds 94%, and for the rural population stands at around 82%. This gap suggests that, at the current stage of energy development, the main challenge is no longer the absence of electrification at the national level, but rather its uneven spatial distribution. In many countries, electricity access in urban centers is nearly universal, whereas rural areas remain relatively underserved.

The estimation of the urban–rural electricity access gap indicates that in a significant number of countries this disparity is small or negligible; however, in others it remains substantial. The largest urban–rural gaps are observed primarily in Africa and in certain low-income economies, where energy infrastructure development is concentrated in urban areas. This implies that the next phase of global electrification will be determined less by the expansion of urban networks and more by the systematic electrification of rural regions.

To deepen the structural analysis, a correlation assessment was conducted. The results indicate that overall electricity access is most strongly associated with rural access levels. The high positive correlation suggests that the primary driver of improvements in national electrification rates is the expansion of rural electrification. At the same time, urban access in many countries is already close to saturation, limiting its marginal contribution to further increases in overall access.

This finding leads to an important policy implication: one of the key priorities of global energy policy should be the expansion of rural energy inclusion.

Based on electricity access levels, three stages of energy development can be distinguished. The first stage corresponds to energy poverty, where a significant share of the population lacks access to electricity. The second stage represents the energy transition phase, characterized by increasing overall access alongside persistent spatial and social inequalities. The third stage corresponds to universal electrification, where nearly the entire population is connected to electricity networks.

This classification shows that most countries in Europe, North America, and East Asia have already reached the stage of universal access, while several countries in Africa and South Asia remain in the first or second stages of electrification.

To identify the economic foundations of cross-country differences in electricity access, an econometric estimation was conducted in which the dependent variable is the overall level of electricity access, while the explanatory variables include GDP per capita, electricity tariffs, and rural electricity access.

The estimation results indicate that among the examined factors, rural electrification exerts the strongest effect. The findings show that a one percentage point increase in rural access is associated with approximately a 0.65 percentage point increase in overall electricity access. This confirms that the primary constraint on global electrification remains the uneven development of rural energy infrastructure.

At the same time, The econometric results indicate a positive but statistically insignificant relationship between GDP per capita and electricity access, suggesting that while higher income levels may facilitate infrastructure development, they do not constitute a primary determinant of access in the cross-country context. This finding suggests that countries with higher levels of economic development possess greater capacity to finance the construction, modernization, and spatial expansion of electricity infrastructure. In other words, higher income levels increase not only household purchasing power but also the ability of both the public and private sectors to support universal electrification.

The coefficient on electricity tariffs is also positive. Although at first glance the positive association between higher tariffs and higher access levels may appear counterintuitive, in a cross-country context it reflects a different economic logic. Countries with higher tariff levels are often characterized by more developed infrastructure, higher income levels, greater cost recovery, and more mature energy markets. Therefore, this result should not be interpreted as evidence of the social desirability of higher prices, but rather as an indication that more advanced and investment-intensive energy systems tend to exhibit both higher access levels and, in many cases, higher final tariffs.

Overall, the econometric findings reinforce the conclusion that rural electrification is the key determinant of electricity access.

The empirical results complement the comparative tariff analysis and demonstrate that international differences in the electricity sector should be evaluated across at least three interrelated dimensions: price, access, and spatial equity. While tariff analysis reveals competitive and institutional differences across countries and regions, the access-based and econometric analysis identifies the structural factors that determine the inclusiveness of energy systems.

From this perspective, effective electricity policy should simultaneously address tariff stability, infrastructure modernization, and—most importantly—the expansion of energy access in rural areas.

The findings indicate that in developing countries, the primary constraint on electricity access is not tariff levels per se, but rather the spatial availability of energy infrastructure. In particular, rural electrification emerges as the central driver of overall access.

Accordingly, energy policy should prioritize the expansion of rural electrification as the main pathway toward achieving universal electricity access. At the same time, tariff policy should be designed in conjunction with social protection mechanisms and infrastructure investments, ensuring both affordability for consumers and the financial sustainability of the energy system.

Conclusion

The results of this study demonstrate that electricity tariff dynamics and access levels are shaped by a complex interplay of multiple factors, where both economic development and the structural and institutional characteristics of energy systems play a crucial role. The comparative analysis for the period 2022–2025 reveals the emergence of distinct tariff subregions within the post-Soviet space, reflecting differences in resource endowments, regulatory models, and levels of market development.

The empirical findings confirm that rural electrification exerts the most significant positive influence on electricity access, while GDP per capita shows a positive but statistically insignificant association in the estimated model. At the same time, the impact of tariff levels is not uniform and depends on country-specific institutional and market conditions. This suggests that identical tariff policies may produce different socio-economic outcomes across countries.

The regional analysis indicates that the South Caucasus is characterized by a relatively stable tariff environment, albeit with notable internal differences. Armenia maintains a comparatively high but stable tariff position, largely driven by a regulated system and a diversified energy mix. In contrast, the low tariff levels observed in Central Asian countries are often associated with subsidy-based policies, which may constrain long-term investment capacity and hinder infrastructure modernization.

Overall, the study confirms that electricity tariffs should be interpreted not merely as price indicators, but as composite measures of economic efficiency, social affordability, and energy security. The limitations of the study—particularly those related to data comparability and the cross-sectional nature of the model—highlight the need for future research based on dynamic and panel data approaches.

The findings of the study allow for the formulation of several policy recommendations.

First, it is essential to develop a balanced tariff policy that simultaneously ensures social affordability and the financial sustainability of energy companies. Excessively low tariffs may restrict investment flows and delay infrastructure modernization, while sharp tariff increases may exacerbate energy poverty.

Second, targeted subsidy mechanisms should be implemented to support vulnerable groups, replacing broad and untargeted subsidies that may distort market efficiency.

Third, investment in energy infrastructure should be strengthened, particularly in rural and remote areas where electrification levels remain limited. Expanding rural electrification can significantly improve overall access and contribute to economic development.

Fourth, regional energy cooperation should be enhanced, including the expansion of cross-border transmission networks and the deepening of electricity trade. While tariff differentials may create opportunities for mutually beneficial cooperation, their realization requires coordinated institutional and technical policies.

Fifth, the development of renewable energy and the diversification of energy systems should be promoted in order to reduce vulnerability to external shocks and ensure long-term price stability.

In conclusion, effective energy policy must integrate market mechanisms, social protection, and regional integration in order to ensure the development of sustainable, affordable, and competitive energy systems.

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ԷԼԵԿՏՐԱԷՆԵՐԳԻԱՅԻ ՍԱԿԱԳՆԵՐԻ ԴԻՆԱՄԻԿԱՆ ԵՎ ՏԱՐԱԾԱՇՐՋԱՆԱՅԻՆ ԷՆԵՐԳԵՏԻԿ ՀԱՄԱԳՈՐԾԱԿՑՈՒԹՅԱՆ ՏՆՏԵՍԱԿԱՆ ԳՈՐԾՈՆՆԵՐԸ

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Սույն հոդվածը ուսումնասիրում է էլեկտրաէներգիայի սակագների դինամիկան և տարածաշրջանային էներգետիկ համագործակցության տնտեսական պայմանավորող գործոնները՝ առանձնահատուկ ուշադրություն դարձնելով հետխորհրդային երկրներին և Հարավային Կովկասին 2022–2025 թվականների ժամանակահատվածում: Վերլուծությունը հիմնված է համակցված տվյալների բազայի վրա, որը ձևավորվել է միջազգային աղբյուրներից, այդ թվում՝ Միջազգային էներգետիկ գործակալությունից (IEA), Համաշխարհային բանկից և գլոբալ էլեկտրաէներգիայի գների տվյալների շտեմարաններից:

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ELECTRICITY TARIFF DYNAMICS AND THE ECONOMIC DETERMINANTS OF REGIONAL ENERGY COOPERATION

Մեթոդաբանական շրջանակը ներառում է համեմատական վիճակագրական վերլուծություն, ժամանակաշարերի գնահատում, երկրների խմբային համեմատություններ և խաչաձև կտրվածքով տնտեսագիտական մոդելավորում: Էլեկտրաէներգիայի սակագների դինամիկան գնահատվում է ինդեքսային և հարաբերական փոփոխության ցուցանիշների միջոցով, իսկ հասանելիության կառուցվածքային տարբերությունները ուսումնասիրվում են էլեկտրաէներգիայի հասանելիության ինդեքսի (Electricity Access Index, EAI) միջոցով, որը ներառում է ընդհանուր, քաղաքային և գյուղական էլեկտրիֆիկացման մակարդակները: Էլեկտրաէներգիայի հասանելիության հիմնական որոշիչները բացահայտելու նպատակով կիրառվել է բազմագործոն ռեգրեսիոն մոդել:

Ստացված արդյունքները վկայում են հետխորհրդային տարածքում սակագնային հստակ ենթատարածքների ձևավորման մասին՝ բարձր գների գոտի (Բալթյան երկրներ), միջին գների գոտի (Հարավային Կովկաս) և ցածր գների գոտի (Կենտրոնական Ասիա): Էմպիրիկ արդյունքները ցույց են տալիս, որ գյուղական էլեկտրիֆիկացումը հանդիսանում է էլեկտրաէներգիայի հասանելիության հիմնական որոշիչը, մինչդեռ մեկ շնչին ընկնող ՀՆԱ-ն և սակագների մակարդակը վիճակագրորեն նշանակալի ազդեցություն չեն ցուցաբերում: Հայաստանը տարածաշրջանում պահպանել է համեմատաբար կայուն, սակայն համեմատաբար բարձր սակագնային դիրք, ինչը պայմանավորված է կարգավորվող գնագոյացման համակարգով և էներգետիկ աղբյուրների դիվերսիֆիկացված կառուցվածքով: Հետազոտության արդյունքները ցույց են տալիս, որ էլեկտրաէներգիայի սակագների դինամիկան ձևավորվում է ռեսուրսային ապահովվածության, շուկայի կառուցվածքի, կարգավորող ինստիտուտների և տարածաշրջանային ինտեգրման գործընթացների համակցված ազդեցության ներքո: Հոդվածում ընդգծվում է նպատակային սակագնային քաղաքականության, ենթակառուցվածքային ներդրումների և միջսահմանային էներգետիկ համագործակցության կարևորությունը՝ էներգիայի մատչելիության, արդյունավետության և երկարաժամկետ էներգետիկ անվտանգության ապահովման տեսանկյունից:

Բանալի բառեր. էլեկտրաէներգիայի սակագներ, էներգետիկ համագործակցություն, էլեկտրաէներգիայի հասանելիություն, հետխորհրդային երկրներ, Հարավային Կովկաս, էներգետիկ տնտեսագիտություն:

ДИНАМИКА ТАРИФОВ НА ЭЛЕКТРОЭНЕРГИЮ И ЭКОНОМИЧЕСКИЕ ФАКТОРЫ РЕГИОНАЛЬНОГО ЭНЕРГЕТИЧЕСКОГО СОТРУДНИЧЕСТВА

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ELECTRICITY TARIFF DYNAMICS AND THE ECONOMIC DETERMINANTS OF REGIONAL ENERGY COOPERATION

В статье проведено комплексное исследование динамики тарифов на электроэнергию и факторов, определяющих региональное энергетическое сотрудничество в постсоветских странах и регионе Южного Кавказа за период 2022–2025 гг. Эмпирическая база исследования сформирована на основе сопоставления данных международных источников, включая Международное энергетическое агентство (IEA), Всемирный банк и глобальные базы данных цен на электроэнергию.

Методологическая основа исследования включает сравнительный статистический анализ, анализ временных рядов, межстрановые и межгрупповые сопоставления, а также кросс-секционное эконометрическое моделирование. Динамика изменения тарифов оценивается с использованием индексных и относительных показателей, тогда как структурные различия в доступе к электроэнергии анализируются с применением Индекса доступа к электроэнергии (Electricity Access Index, EAI), включающего показатели общего, городского и сельского уровня электрификации. Для выявления ключевых факторов доступа к электроэнергии используется многомерная регрессионная модель.

Полученные результаты свидетельствуют о формировании выраженных тарифных субрегионов в постсоветском пространстве: зоны высоких цен (страны Балтии), средних цен (Южный Кавказ) и низких цен (Центральная Азия). Эмпирический анализ показывает, что уровень сельской электрификации является ключевым фактором, определяющим общий уровень доступа к электроэнергии, в то время как ВВП на душу населения и уровень тарифов не оказывают статистически значимого влияния. Армения характеризуется относительно стабильной, но сравнительно высокой тарифной позицией, что обусловлено регулируемой системой ценообразования и диверсифицированной структурой энергетического баланса.

Результаты исследования показывают, что динамика тарифов формируется под воздействием совокупности факторов, включая ресурсную обеспеченность, структуру рынка, институционально-регуляторную среду и процессы региональной интеграции. Подчеркивается необходимость разработки сбалансированной тарифной политики, расширения инвестиций в инфраструктуру и углубления трансграничного энергетического сотрудничества как ключевых условий обеспечения доступности, эффективности и долгосрочной энергетической безопасности.

***Ключевые слова*:** тарифы на электроэнергию, энергетическое сотрудничество, доступ к электроэнергии, постсоветские страны, Южный Кавказ, экономика энергетики.

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THE ROLE AND SIGNIFICANCE OF ARMENIA'S SOVEREIGN CREDIT RATING IN THE DEVELOPMENT OF THE GOVERNMENT BOND MARKET

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Abstract

Sovereign credit ratings currently represent some of the most important indicators in global financial markets, having a significant influence on government financing conditions and investment decisions. In the case of the Republic of Armenia, these ratings are of particular importance given the current stage of economic development and the existing challenges in public debt management. However, delays in market response (1–2 months) and the limited development of the domestic financial market constrain the effectiveness of the financial system's functioning. A comparative analysis shows that in countries such as Georgia and the Baltic states (Latvia and Lithuania), the transmission of rating signals to the market occurs more rapidly and more efficiently, which is explained by higher levels of institutional reforms and the quality of financial governance. All of this underscores the need for the implementation of consistent reforms in Armenia, the improvement of the public debt management strategy, and the enhancement of information transparency in the financial market. These steps will make it possible to improve the country's sovereign ratings, reduce borrowing costs, and ensure sustainable long-term economic growth.

***Keywords*:** Sovereign credit rating, government bonds, financial stability, risk premium, debt management, bond yields.

Introduction

The modern global financial environment imposes higher requirements on the investment decision-making process, emphasizing the need for transparency, objectivity, and rigorous analysis. Under these conditions, sovereign credit ratings provided by leading international rating agencies—Moody's, Standard & Poor's, and Fitch—become key signals for financial markets. They reflect a country's financial and economic condition, credit risks, and the government's ability to meet its debt obligations. Ratings represent a decisive factor not only in investment decision-making but also in the formation of borrowing costs for governments. Sovereign ratings constitute a classification system based on a wide range of criteria, including fiscal indicators (public debt, budget deficit, monetary policy), economic factors (economic growth, export levels), as well as structural and institutional characteristics (political stability, legal environment, quality of governance). The combination and analysis of these diverse criteria allow rating agencies to assess a country's long-term financial sustainability and risks, which in turn has an additional impact on capital markets. Credit ratings serve as an important tool for assessing a country's creditworthiness and financial stability. The outlooks that accompany them—"stable," "positive," or "negative"—signal possible changes in the level of investor confidence and the direction of future rating revisions. These indicators serve as important tools for investors when assessing risks, forecasting government bond yields, and managing their investment portfolios accordingly. In the case of the Republic of Armenia, sovereign ratings are of particular importance, as the country is undergoing a complex phase of recovery and reform, in which public debt management and the provision of financial stability constitute key fundamental factors. The public debt management strategy, which is regularly updated and published by the Government of Armenia, is aimed at the timely and efficient mobilization of borrowed funds, the reduction of financial risks, and the optimization of debt servicing costs. The aforementioned rating agencies, despite certain methodological differences, unanimously emphasize the importance of economic and political risks, the impact of which is particularly pronounced for emerging economies. Nevertheless, indicators such as control over public debt, fiscal discipline, political stability, and the implementation of structural reforms constitute key components in the formation of sovereign ratings. The relationship between government ratings and government bond yields represents a multifaceted interaction that directly affects the stability of a country's financial markets and investment flows. A high rating generally contributes to lower bond yields by acting as a signal of reduced risk, which stimulates capital inflows and ensures more accessible financing. Conversely, a rating downgrade increases borrowing costs, which may constrain a government's financial capacity and affect macroeconomic performance. In this context, the present article is aimed at conducting an in-depth quantitative analysis of the relationship between Armenia's sovereign ratings and the yields on 364-day government bonds over the period 2010–2025. The results of the study not only complement the academic literature on sovereign ratings and public debt management but may also serve as a tool for developing effective fiscal policy strategies and financial market development, thereby ensuring Armenia's financial stability and favorable prospects for economic growth.

This study is relevant both for the academic community and for practical policy-making, strengthening the link between theory and the implementation of financial policy, particularly in developing countries, where financial market infrastructure and the role of rating agencies continue to expand steadily [1, 2].

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THE ROLE AND SIGNIFICANCE OF ARMENIA'S SOVEREIGN CREDIT RATING IN THE DEVELOPMENT OF THE GOVERNMENT BOND MARKET

Conflict Setting

The aim of this study is to examine the significance of sovereign credit ratings within the context of Armenia's ongoing economic recovery and structural reforms. Effective public debt management and financial stability are pivotal for sustainable development and play a decisive role in shaping investment decisions and borrowing conditions.

This research utilizes official data from the Government of Armenia and reports from leading international rating agencies to conduct a rigorous quantitative assessment of the determinants of sovereign ratings, including fiscal performance, economic indicators, and institutional factors. Additionally, the study investigates the relationship between sovereign ratings and 364-day government bond yields, exploring their influence on capital flows, financing conditions, and overall macroeconomic performance.

The findings offer evidence-based insights for policymakers and investors, illuminating the complex interactions between sovereign ratings, financial market stability, and long-term economic growth, thereby contributing to informed fiscal strategy and investment planning in a transitioning economy.

Research Results

In the modern global financial environment, sovereign credit ratings are a key factor shaping investment behavior, guiding decisions of capital market participants and influencing perceptions of a country's creditworthiness, financial reliability, and external financing conditions, as well as the signals transmitted to the market. Government bonds are often regarded as instruments with relatively low risk and stable returns, especially in emerging economies, where investors closely monitor the assessments of rating agencies such as Moody's, Standard & Poor's, and Fitch. These assessments are based on a comprehensive set of criteria, including the level of public debt, budgetary discipline, stability of economic growth, external risks, effectiveness of monetary policy, and the quality of institutional governance.

The Republic of Armenia, as a small and open emerging economy, is sensitive to changes in sovereign ratings and their impact on the financial market.

The data analysis shows a significant negative correlation ($r \approx -0.61$) between Armenia's sovereign rating and the yield on 364-day government bonds, indicating a reduction in short-term financing costs when the rating improves. This correlation suggests that as the rating improves, bond yields decline because investors perceive a reduction in the risk premium as a sign of safer lending. At the same time, a downgrade is accompanied by an increase in bond yields, reflecting a higher risk premium.

Secondly, the structure of investors and insufficiently developed market practices reduce market efficiency and slow the speed of reaction. This delay lowers the predictability and transparency of market processes, which in the long run may negatively affect the stability of the investment environment.

Using Armenia as an example makes it possible to more clearly illustrate how rating factors and perceived sovereign risk influence external financing conditions. Despite the fact that since 2006 Armenia has been classified within the non-investment-grade ("speculative") category, a certain level of confidence in international markets has been maintained, as evidenced by a number of successful Eurobond issuances.

The main Eurobond issuances include the following:

- In 2013, a 7-year issuance with a risk spread of 413.2 basis points;
- In 2015, a 10-year issuance with a yield of 7.15 percent and a risk spread of 551.8 basis points.,
- In 2019, an issuance with a yield of 3.95 percent.
- In 2021, an issuance of USD 750 million with a coupon rate of 3.6 percent and a yield of 3.875 percent;
- In 2025, an issuance with a yield of 7.1 percent.

The yields of these issuances were formed mainly under the influence of two key factors.

1. The yield on U.S. Treasury securities with a comparable maturity (benchmark rate).
2. Armenia's sovereign risk premium (country risk premium).

Although the sovereign rating reflects many macroeconomic, debt-related, and political indicators, government bond yields may also be influenced by additional factors that are not fully captured by rating agencies. These elements include regional uncertainty, short-term political events, and specific features of financial market regulation. Clarifying these factors is important for achieving a more comprehensive understanding of the dynamics of government bond yields.

Taken together, these factors shape investors' risk expectations and the cost of financing. Fluctuations in yields on Armenian Eurobonds indicate that both the assessment of external risks and the quality of domestic economic governance play an important role in building confidence in the country in international financial markets.

Demand indicators for Armenia's Eurobonds also reflect growing confidence among international investors, namely: on average more than 200 investors are attracted; total demand amounts to approximately USD 2.7 billion; the highest demand was recorded in 2021 at USD 3 billion; the lowest demand was observed for the 2025 issuance at USD 2.6 billion.

These data indicate a gradual improvement in Armenia's credit profile and the strengthening of the country's position in international financial markets.

The process of yield formation for Armenian Eurobonds is considered an important component in assessing the risks of financial instruments in emerging markets under systemic trends in international financial markets. In this context, external factors play a significant role, within which market activity takes place, substantially influencing bond yields and risk premiums.

In the first quarter of 2025, important developments occurred in the field of public debt management of the Republic of Armenia. On March 12, 2025, the government successfully placed Eurobonds in the amount of USD 750 million with a 10-year maturity, at a placement yield of 7.10 percent and a coupon rate of 6.75 percent. This issuance, which became the fifth foreign-currency sovereign bond issuance by Armenia on the international capital market, exceeded the initially planned volume of USD 500 million by an additional USD 250 million. The objective was to reduce pressure on the domestic debt market and strengthen balance-of-payments sustainability through the attraction of external financial flows and the replenishment of international reserves. Actual proceeds amounted to 287.4 billion drams (USD 731.4 million), indicating high market efficiency and strong investor interest.

The increase in yields compared to 3.875 percent in 2021 requires in-depth analysis. In 2021, the yield on 10-year U.S. Treasury bonds was 1.039 percent, while Armenia's spread amounted to 2.836 percentage points. In 2025, the yield on U.S. bonds of the same maturity increased to 4.24 percent, while Armenia's spread remained almost unchanged at 2.86 percentage points. These data indicate the stability of Armenia's risk premium in the perception of international investors, despite a significant increase in global interest rates. Thus, the rise in yields is mainly due to the tightening of global monetary policy rather than a deterioration of Armenia's credit profile.

In addition, on March 24, 2025, the Government of the Republic of Armenia redeemed Eurobonds issued in 2015 in the amount of USD 313.166 million, which confirms the soundness of the public debt management strategy and the effectiveness of the policy of timely repayment of existing obligations.

These complex processes are regarded as important indicators of investor confidence and the stability of public debt management. Strategic approaches of rating agencies can serve as a basis for improving the country's credit rating by ensuring predictability, mitigating risks, and maintaining a balanced policy toward capital markets.

For a comprehensive analysis, it is necessary to conduct comparative studies of government bond yield dynamics in emerging economies, especially those with sovereign credit ratings similar or close to that of Armenia. Such an approach makes it possible to distinguish between the impact of domestic macroeconomic factors and international financial conditions, as well as to develop a deeper understanding of investor perceptions of financial risks related to Armenia in the global market context.

For the comparative analysis, Georgia and the Baltic states (Latvia and Lithuania) were selected due to differences in the level of financial market development, institutional maturity, and the availability of comparable long-term data on bond yields and rating assessments. The analysis showed that the financial markets of these countries differ in their level of maturity and demonstrate varying responses to rating signals. In Georgia, a moderate relationship between sovereign ratings and government bond yields is observed, with a correlation coefficient of –0.54, and the average transmission lag of rating signals to the market is about one month. In the Baltic states, sovereign ratings are higher according to Moody's (A3/A– and A2/A), which is reflected in lower yield levels ranging from 1.5 to 3.0 percent and from 1.0 to 2.8 percent, respectively, as well as in a stronger relationship with yields, with correlation coefficients of –0.72 and –0.75. In addition, in these countries the transmission of rating signals to the market occurs more rapidly, within one month or less, due to deep financial market integration, information transparency, and a high level of institutional capacity.

These data indicate that market size, governance quality, and the efficiency of information flows play an important role in the speed and strength of the impact of rating signals on the market, which should be taken into account in financial policy and governance reforms in emerging economies, including Armenia.

Table 1

Country	Moody's Rating	Yield (%)	Correlation (r)	Average response Time(month)
Armenia	B1 / B+	6,5 - 10,5	–0,61	1,5
Georgia	Ba2 / BB	5,2 - 8,8	–0,54	1
Latvia	A3 / A-	1,5 - 3,0	–0,72	≤1
Lithuania	A2 / A	1,0 - 2,8	–0,75	≤1

Significant differences are also observed in the size of the risk premium. In Armenia, the average risk premium amounts to 3–4 percent, reflecting a relatively high level of risk. Georgia is in approximately the same range at 2.5–3.5 percent, indicating an above-average level of confidence. Indeed, the observed relationship between sovereign ratings and the level of the risk premium is expected: countries with higher sovereign ratings (the Baltic states) exhibit a lower risk premium, reflecting a high level of institutional stability and investor confidence. By contrast, Armenia and Georgia have higher risk premia, which corresponds to a more moderate level of confidence and less developed financial markets. Thus, differences in risk premia are consistent with sovereign ratings and the degree of financial market maturity.

Table 2

Country	Risk premium (%)	Level of investor confidence
Armenia	3,0 - 4,0	Medium
Georgia	2,5 - 3,5	Above average
Latvia	1,0 - 1,5	High
Lithuania	1,0	High

The presented statistical data and analysis show that rating agency assessments not only reflect a country's financial and economic condition but also play an important signaling role for the market, guiding investment decisions and contributing to financial stability. At the same time, the depth and dynamics of this influence depend on the level of institutional market development, the effectiveness of financial governance, and the transparency of information flows. In the case of Armenia, key challenges remain the need to ensure rapid and efficient information transmission, the development of secondary markets, and the institutional strengthening of financial governance systems. Periodic revision of the public debt management strategy by the Government of the Republic of Armenia, along with increased transparency, can be key steps toward enhancing market confidence and strengthening financial stability. Georgia's experience shows that monetary policy stability, consistency of structural reforms, and the development of institutional market mechanisms contribute to rating stabilization and the reduction of financial risks. The example of the Baltic states highlights that long-term maintenance of high credit ratings is possible only through deep institutional reforms, the application of European governance standards, and broad integration of capital markets.

These insights and statistical data provide an important foundation for the development of Armenia's financial policy and the improvement of the investment climate, which will help reduce financing costs, increase investor confidence, and ensure long-term prospects for sustainable economic growth. In the context of increasing globalization and growing instability in international financial markets, sovereign credit ratings acquire particular importance for developing economies. They not only reflect a country's current financial and economic position but also serve as an important signal for international investors, shaping expectations regarding risk, government bond yields, and the cost of attracting external capital.

The study conducted using the Republic of Armenia as a case study made it possible to identify a stable statistical relationship between changes in the sovereign rating and government bond yields, with a correlation coefficient of –0.61. This confirms the existence of a direct impact of ratings on market borrowing rates, even under conditions of limited liquidity and institutional maturity of the market. At the same time, an important scientific result is that the increase in yields in recent years has been driven primarily by global macroeconomic conditions (rising interest rates in the United States and the European Union), rather than by a deterioration in Armenia's domestic credit profile. The stability of the risk premium (approximately 2.86 percentage points in 2025) confirms sustained investor confidence in the country.

The scientific novelty of the research is expressed as follows:

- for the first time, a systematic analysis of the dependence of Armenian Eurobond yields on rating signals has been conducted in comparison with similar countries in the region;
- differences in the speed of market reaction have been identified: Armenia demonstrates a delayed response (up to 1.5 months) compared to Latvia and Lithuania (up to 1 month), which is associated with lower information transparency and market development;
- the conservative perception of Armenia by rating agencies has been identified, while investor behavior reflects a more positive assessment of the country's credit risk.

A comparative analysis was also conducted with other post-Soviet countries (Georgia, Latvia, and Lithuania), which showed that:

- higher ratings and greater institutional maturity ensure lower yield levels (1–3%) and a stronger correlation between ratings and market interest rates;
- institutional infrastructure (transparency, speed of information transmission, and development of secondary markets) plays a decisive role in transforming rating signals into investment decisions.

Thus, despite Armenia's current classification as a country with a "speculative" rating, there remains significant potential for improving its credit profile. This is driven by:macroeconomic stability; a consistent public debt management policy; positive dynamics in demand for sovereign bonds; a stable external position and reserve policy.

Conclusion

To enhance the transparency and predictability of fiscal policy, it is recommended to regularly publish public debt management strategies and conduct independent audits. This strengthens investor confidence, reduces financial risks, and improves the effectiveness of budgetary management.

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ՀԱՅԱՍՏԱՆԻ ՍՈՒՎԵՐԵՆ ՎԱՐԿԱՆԻՇԻ ԴԵՐԸ ԵՎ ՆՇԱՆԱԿՈՒԹՅՈՒՆԸ ՊԵՏԱԿԱՆ ՊԱՐՏԱՏՈՄՍԵՐԻ ՇՈՒԿԱՅԻ ԶԱՐԳԱՑՄԱՆ ԳՈՐԾՈՒՄ

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Համեմատական վերլուծությունը ցույց է տալիս, որ Վրաստանի և Բալթյան երկրների (Լատվիա և Լիտվա) պարագայում վարկանիշային ազդանշանների փոխանցումը շուկային կատարվում է ավելի արագ և արդյունավետ, ինչը բացատրվում է ինստիտուցիոնալ բարեփոխումների բարձր մակարդակով և ֆինանսական կառավարման որակով: Սրանք ընդգծում են Հայաստանի համար համաչափ բարեփոխումներ իրականացնելու, պետական պարտքի կառավարման ռազմավարությունը բարելավելու և ֆինանսական շուկայում տեղեկատվության թափանցիկությունը բարձրացնելու անհրաժեշտությունը:

Բանալի բառեր. Սուվերեն վարկանիշ, պետական պարտատոմսեր, ֆինանսական կայունություն, ռիսկային պրեմիա, պարտքի կառավարում, պարտատոմսերի եկամտաբերություն

РОЛЬ И ЗНАЧЕНИЕ СУВЕРЕННОГО КРЕДИТНОГО РЕЙТИНГА АРМЕНИИ В РАЗВИТИИ РЫНКА ГОСУДАРСТВЕННЫХ ОБЛИГАЦИЙ

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Сравнительный анализ показывает, что в таких странах, как Грузия, а также в странах Балтии (Латвия и Литва), передача рейтинговых сигналов на рынок происходит быстрее и эффективнее, что обусловлено более высоким уровнем институциональных реформ и качества финансового управления. Все это подчеркивает необходимость проведения последовательных реформ в Армении, совершенствования стратегии управления государственным долгом и повышения информационной прозрачности финансового рынка.

Ключевые слова: суверенный рейтинг, государственные облигации, финансовая стабильность, премия за риск, управление долгом, доходность облигаций.

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TRENDS IN WATER USE AND WATER STRESS IN ARMENIA (2011–2025): INTEGRATING CLIMATE DYNAMICS, SYSTEM EFFICIENCY, AND RESOURCE MANAGEMENT

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Abstract

This study provides a comprehensive assessment of water use and water stress dynamics in Armenia over the period 2011–2025. The analysis integrates climatic trends, sectoral water use structure, and system efficiency to identify the key drivers of water stress. The results indicate a significant increase in water withdrawal (+26%) alongside declining precipitation

(−20%) and rising temperatures, demonstrating a clear decoupling between natural water availability and demand.

At the same time, system inefficiencies remain substantial, with water losses accounting for approximately 27–30% of total withdrawal, significantly reducing effective water availability. Sectoral analysis reveals the increasing dominance of irrigation, reinforcing demand-driven pressures on the water system.

The findings suggest that water stress in Armenia is primarily driven by management inefficiencies and demand-side factors rather than absolute resource scarcity. Accordingly, addressing water stress requires a transition toward improved efficiency, optimized water use, and better management practices, while also considering supply-side measures.

Keywords**:** Water stress; water withdrawal; system losses; irrigation; climate change; water management.

Introduction

Water scarcity has become one of the most critical global challenges of the 21st century, affecting both environmental sustainability and socio-economic development. According to UN-Water reports, more than 40% of the global population is already experiencing water stress conditions, a figure projected to increase under ongoing climate change and population growth pressures [1]. Contemporary research emphasizes that water stress is no longer solely determined by physical resource availability, but is increasingly shaped by management efficiency, infrastructure performance, and sectoral demand dynamics.

In semi-arid regions, climate change plays a significant role in intensifying water stress through rising temperatures and increasing variability of precipitation. Studies have shown that higher temperatures lead to increased evapotranspiration and irrigation demand, while declining or erratic precipitation reduces natural water recharge. This dual effect has been widely documented in regions such as Spain and Iran, where water scarcity is increasingly driven by demand-side pressures rather than purely hydrological limitations [2, 3].

Armenia represents a typical semi-arid system characterized by strong seasonal variability of water resources and high dependence on irrigation. Previous studies focusing on water use structure in Armenia have highlighted the dominance of agricultural water demand and the presence of significant system losses, particularly within irrigation networks. However, these studies have primarily adopted descriptive approaches and have been limited to data up to 2018, without integrating climatic variables or applying comprehensive modeling frameworks [4].

Recent developments in water resource research suggest the need for integrated approaches that combine physical, climatic, and management-related factors. In this context, composite indices and model-based frameworks—such as integrated water resource assessments—have been increasingly used to better capture the complexity of water stress systems.

The present study builds upon previous empirical analyses by extending the temporal scope to 2026 and introducing an integrated analytical framework that combines climate dynamics, system efficiency, and sectoral structure. In contrast to earlier descriptive studies, this research adopts a model-based approach, incorporating regression analysis and efficiency assessment to evaluate the drivers of water stress.

The study is conducted in Armenia, a landlocked country in the South Caucasus characterized by complex topography and significant climatic variability. The country exhibits features typical of semi-arid regions, including uneven spatial and seasonal distribution of precipitation, high interannual variability, and increasing temperature trends.

Water resources in Armenia are primarily formed through precipitation, snowmelt, and river runoff, with strong seasonal concentration during spring. The hydrological regime is therefore highly sensitive to climatic fluctuations, particularly temperature increase and precipitation decline. Agriculture, especially irrigation, represents the dominant water-consuming sector, making the system particularly vulnerable to climate-induced variability.

The analysis is based on official national statistics and environmental monitoring data:

- Armstat — annual data on water withdrawal, water use, and sectoral distribution [5];
- National environmental monitoring systems — temperature and precipitation data.

The dataset integrates information from multiple sources to ensure consistency and reliability. Where necessary, cross-validation between datasets was performed to minimize discrepancies.

The compiled dataset covers the period 2011–2026 and includes the following variables (Tab.1).

Table 1

Variable	Unit	Description
Water withdrawal	mln m³	Total volume of abstracted water
Water use	mln m³	Effectively used water
Water losses	mln m³	Difference between withdrawal and use
Sectoral shares	%	Irrigation, domestic, industry, aquaculture
Temperature	°C	Annual average temperature
Precipitation	mm	Annual total precipitation

Data processing involved several steps:

- Data consistency check — ensuring continuity across years;
- Handling missing values — linear interpolation applied where necessary;
- Unit standardization — all water volumes expressed in mln m³;
- Derived variable computation — based on established hydrological relationships

To enable comparative analysis, selected variables were normalized and transformed where appropriate.

The selected period (2011–2026) allows:

- extension of previous studies (limited to 2018);
- inclusion of recent climate trends;
- identification of long-term changes in water use and stress dynamics.

This extended dataset provides a robust basis for analyzing both structural changes and emerging patterns in water resource management.

Conflict Setting

The novelty of this study lies in extending the temporal coverage of water use analysis in Armenia while integrating climatic variability, system efficiency, and sectoral dynamics into a unified framework, which has not been addressed in previous research. The main objectives of the study are:

- to analyze trends in water withdrawal and use (2011–2026),
- to assess the relationship between climate variables and water demand,
- to evaluate system efficiency and water losses,
- to identify the key drivers of water stress using an integrated framework.

Research Results

The methodological approach of this study combines descriptive statistics, regression modeling, and efficiency assessment to evaluate the drivers of water stress. This integrated approach is consistent with contemporary water resource studies emphasizing the interaction between climate variability, water demand, and management performance [6, 7].

The framework is structured around three main components:

- water balance and loss analysis;
- climate–water interaction modeling;
- system efficiency and stress evaluation.

The analysis of the period 2011–2026 reveals a consistent increase in water withdrawal in Armenia, rising from approximately 2438 mln m³ in 2011 to 3080 mln m³ in 2026, representing an increase of approximately 26%. Water use follows a similar trend, increasing from 1738 mln m³ to 2160 mln m³ over the same period [5].

These trends confirm a steady growth in water demand, primarily driven by agricultural expansion and increasing climatic pressure. Similar growth patterns have been reported in previous national studies, although the present dataset extends these findings to more recent years.

Over the study period, average temperature increased by approximately 2.6°C, while annual precipitation declined by approximately 20%. Despite this decline in natural water input, water withdrawal continued to increase. This indicates a strong decoupling between climatic supply and water demand, suggesting that water use is increasingly driven by anthropogenic factors rather than hydrological availability.

Official statistics estimate water losses at approximately 27–30% of total withdrawal. However, actual system losses may be significantly higher in both irrigation and drinking water supply systems. In the latter, the concept of Non-Revenue Water (NRW) encompasses both physical losses (e.g., leakage and seepage) and commercial losses (e.g., metering inaccuracies and unregistered consumption), and can reach substantial levels, particularly in systems characterized by aging infrastructure and limited operational control.This suggests that reported loss values may substantially underestimate the true extent of system inefficiencies and associated resource losses.

Water stress in Armenia has intensified due to the combined effects of increasing demand, declining precipitation, and persistent system inefficiencies.

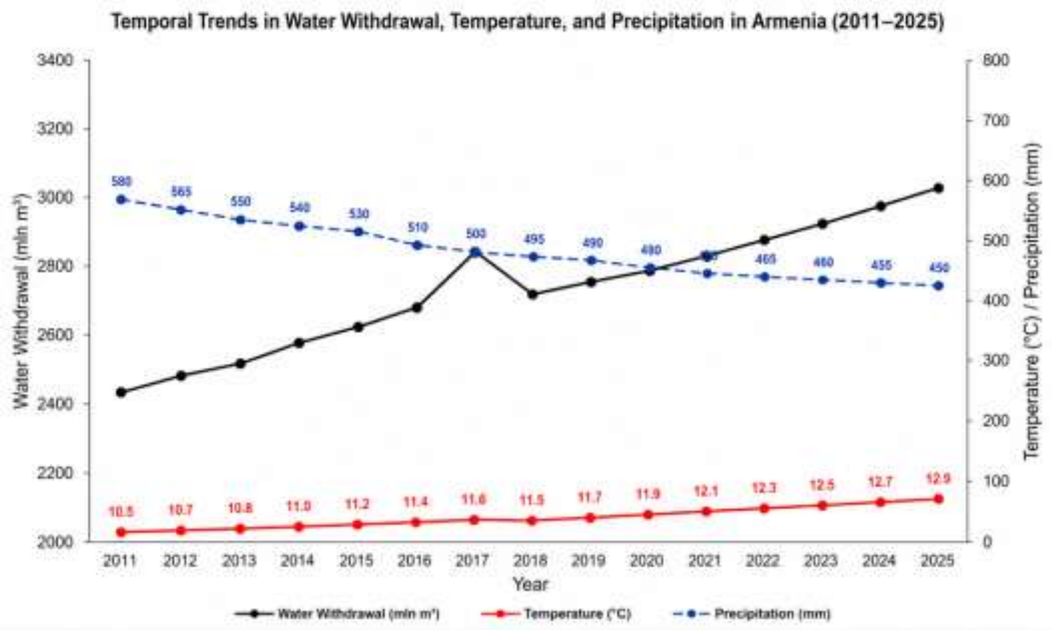
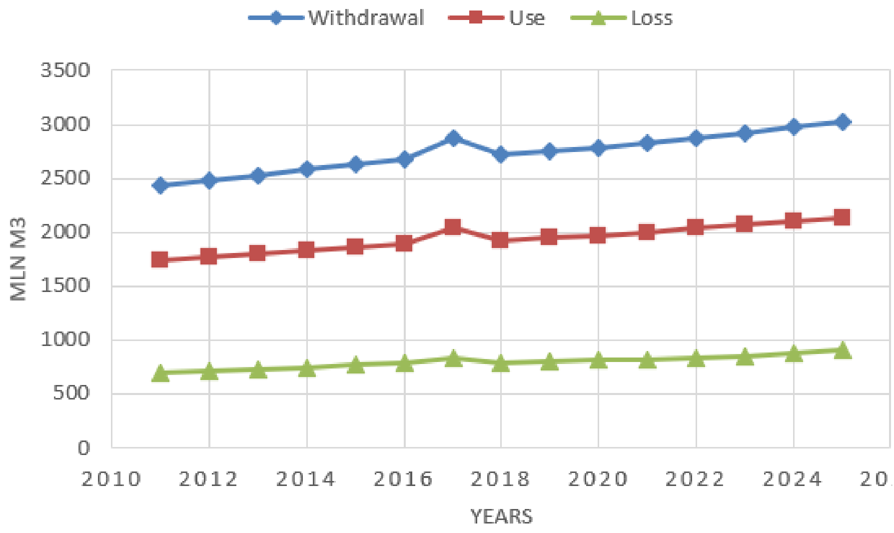


Fig. 1 Temporal trends in water withdrawal, temperature, and precipitation in Armenia (2011–2025), illustrating a clear decoupling between increasing water demand and declining natural water availability

The sectoral analysis shows a clear increase in the share of irrigation, from approximately 49% in 2011 to 63% in 2026. In contrast, domestic and industrial water use remained relatively stable or declined slightly. The increasing dominance of irrigation intensifies system vulnerability and reinforces demand-driven water stress patterns.

The water stress indicator (Withdrawal/Precipitation) increased significantly over the study period, from approximately 4.2 in 2011 to 6.9 in 2025. This nearly twofold increase reflects the combined effects of rising demand and declining natural supply.

Fig. 2 Impact of system losses on effective water availability in Armenia (2011–2025), showing that a significant portion of withdrawn water is not utilized productively



As shown in Fig. 2, a substantial portion of withdrawn water is lost within the system, significantly reducing effective water availability.

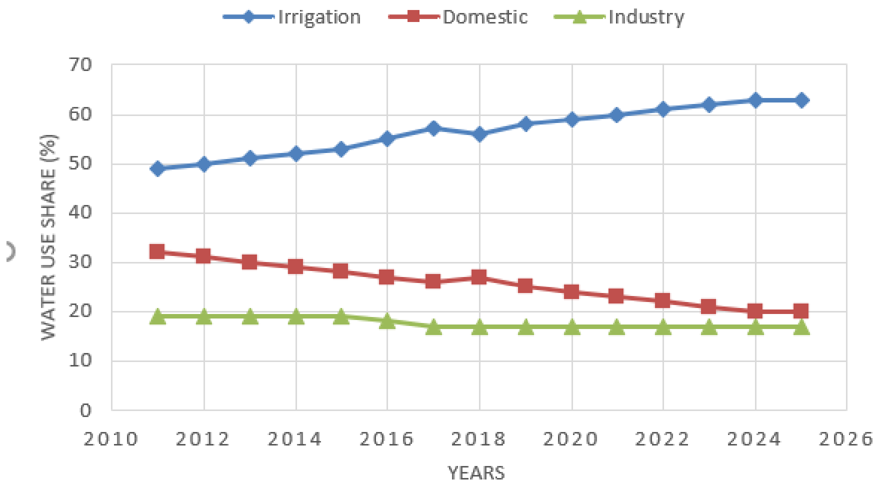
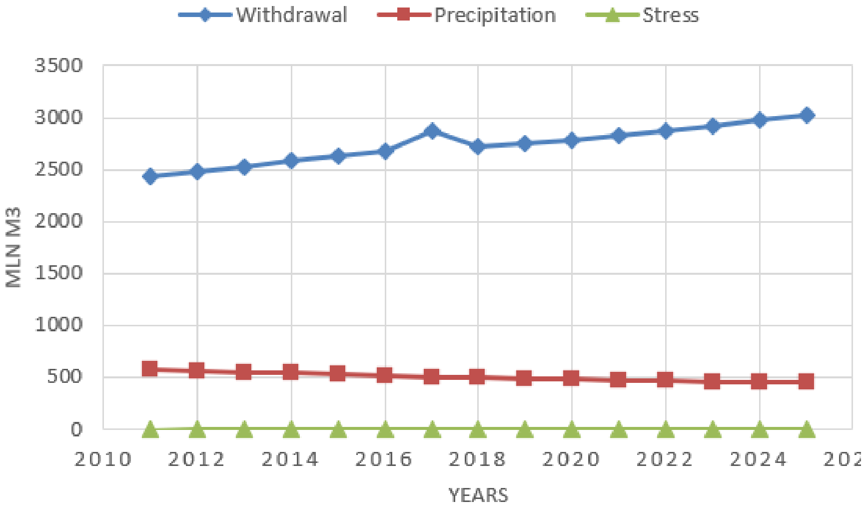


Fig. 3. Evolution of sectoral water use structure in Armenia (2011–2025), highlighting the increasing dominance of irrigation

As shown in Fig. 3, irrigation has become the dominant water use sector, reinforcing demand-driven water stress

Fig. 4. Increasing water stress index in Armenia (2011–2025), reflecting the combined effects of rising water demand and declining precipitation



As shown in Fig. 4, water stress has increased significantly over time, reflecting the combined effects of rising demand and declining natural water availability.

Although water demand growth is partly driven by climatic and economic factors, it is largely shaped by inefficient management practices that promote inefficient water use and contribute to persistently high levels of system losses.

Conclusion

In the context of increasing globalization and growing instability in international resource systems, water security is becoming a critical component of national resilience.

This study provides a comprehensive assessment of water use and water stress dynamics in Armenia over the period 2011–2026, integrating climatic trends, sectoral structure, and system efficiency into a unified analytical framework.

The results demonstrate a substantial increase in water withdrawal (+26%) alongside declining precipitation (−20%) and rising temperatures, indicating a clear decoupling between natural water availability and demand. At the same time, water losses remain persistently high, both in relative terms (27–30%) and in absolute volumes, significantly reducing effective water availability.

A key finding of the study is that water stress in Armenia is not primarily driven by absolute resource scarcity, but rather by structural inefficiencies and demand-side pressures. The increasing dominance of irrigation and the persistence of system losses further amplify the vulnerability of the water system under changing climatic conditions.

Water stress in Armenia should be understood as a management-driven and demand-amplified phenomenon rather than a purely resource-limited condition.

Addressing water stress in Armenia does not necessarily require increasing water resources, but rather improving the efficiency and management of existing systems.

Policy implications

Priority should be given to reducing physical and commercial water losses through:

- rehabilitation of aging infrastructure,
- implementation of leakage detection and control systems,
- improvement of metering and monitoring practices.

Given the dominant role of irrigation, significant gains can be achieved by:

- transitioning to efficient irrigation technologies (e.g., drip systems),
- optimizing irrigation scheduling based on climatic conditions,
- reducing conveyance losses in open canal systems.

Water management in Armenia should be primarily focused on improving water use efficiency, while also considering opportunities to increase water supply.

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TRENDS IN WATER USE AND WATER STRESS IN ARMENIA (2011–2025): INTEGRATING CLIMATE DYNAMICS, SYSTEM EFFICIENCY, AND RESOURCE MANAGEMENT

ՀԱՅԱՍՏԱՆՈՒՄ ՋՐՕԳՏԱԳՈՐԾՄԱՆ ԵՎ ՋՐԱՅԻՆ ՍԹՐԵՍԻ ՄԻՏՈՒՄՆԵՐԸ (2011–2025). ԿԼԻՄԱՅԱԿԱՆ ԴԻՆԱՄԻԿԱՅԻ, ՀԱՄԱԿԱՐԳԱՅԻՆ ԱՐԴՅՈՒՆԱՎԵՏՈՒԹՅԱՆ ԵՎ ՌԵՍՈՒՐՍՆԵՐԻ ԿԱՌԱՎԱՐՄԱՆ ՎԵՐԼՈՒԾՈՒԹՅՈՒՆ

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[2]*Հայաստանի պետական տնտեսագիտական համալսարան*

Սույն ուսումնասիրությունը ներկայացնում է Հայաստանում ջրօգտագործման և ջրային սթրեսի դինամիկայի համապարփակ գնահատում 2011–2025 թվականների համար: Վերլուծությունը միավորում է կլիմայական միտումները, ջրօգտագործման ոլորտային կառուցվածքը և համակարգային արդյունավետությունը՝ բացահայտելու ջրային սթրեսի հիմնական գործոնները:

Արդյունքները ցույց են տալիս ջրառի զգալի աճ (≈26%)՝ տեղումների նվազման (≈20%) և ջերմաստիճանի աճի պայմաններում, ինչը վկայում է բնական ջրային պաշարների և պահանջարկի միջև հստակ տարանջատման մասին: Միաժամանակ, ջրային կորուստները պահպանվում են բարձր մակարդակի վրա (≈27–30%)՝ էապես նվազեցնելով արդյունավետ ջրային հասանելիությունը:

Ոլորտային վերլուծությունը ցույց է տալիս ոռոգման գերակշռության աճ, որը մեծացնում է պահանջարկով պայմանավորված ճնշումը համակարգի վրա:
Ուսումնասիրության արդյունքները վկայում են, որ Հայաստանում ջրային սթրեսը պայմանավորված է ոչ միայն ռեսուրսների սահմանափակությամբ, այլ հիմնականում կառավարման անարդյունավետությամբ և պահանջարկի գործոններով:

Բանալի բառեր. ջրային սթրես, ջրառ, ջրային կորուստներ ոռոգում, կլիմայական փոփոխություն, ջրային կառավարում

ТЕНДЕНЦИИ ВОДОПОТРЕБЛЕНИЯ И ДЕФИЦИТА ВОДЫ В АРМЕНИИ (2011–2025): АНАЛИЗ ДИНАМИКИ КЛИМАТА, ЭФФЕКТИВНОСТИ СИСТЕМЫ И УПРАВЛЕНИЯ РЕСУРСАМИ

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Представлен комплексный анализ динамики водопользования и водного стресса в Armenia за период 2011–2025 гг. Исследование объединяет климатические тенденции, отраслевую структуру водопотребления и эффективность системы с целью выявления ключевых факторов формирования водного стресса.

V.H. Tokmajyan, A.Kh. Markosyan, G.H. Martirosyan, A.K. Harutyunyan

TRENDS IN WATER USE AND WATER STRESS IN ARMENIA (2011–2025): INTEGRATING CLIMATE DYNAMICS, SYSTEM EFFICIENCY, AND RESOURCE MANAGEMENT

Результаты показывают значительный рост водозабора (+26%) на фоне снижения осадков (−20%) и повышения температуры, что свидетельствует о разрыве между природной обеспеченностью водой и спросом. При этом потери воды остаются высокими (≈27–30%), что существенно снижает эффективную доступность водных ресурсов.

Анализ структуры водопользования показывает возрастающую роль орошения, усиливающего давление на водную систему.

Полученные результаты свидетельствуют о том, что водный стресс в Армении обусловлен не столько дефицитом ресурсов, сколько неэффективным управлением и ростом спроса.

Ключевые слова: водный стресс; водозабор; потери воды; орошение; изменение климата; управление водными ресурсами.

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CONTENTS

CONTENTS

CONTENTS